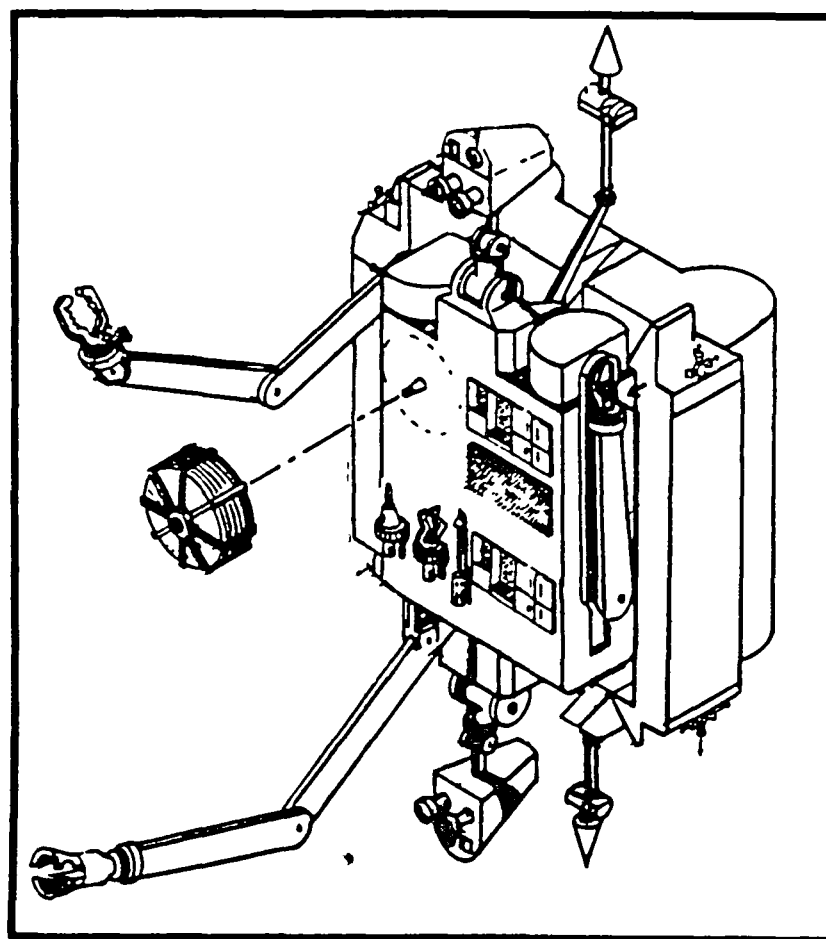


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Final Report
Concept Definition and
Technology Assessment
D483-10027-1

Space Station Automation and Robotics Study

Operator-Systems Interface



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Space Station Automation and Robotics Study

Final Report

Operator - Systems Interface

Conducted for NASA

November 1984

Boeing Aerospace Company
and
Boeing Computer Services Company

N85-33172[#]

Foreword

In May of 1984, NASA initiated an Automation and Robotics Technology Planning Study in response to a mandate from the U S. Congress associated with appropriations for the Space Station.

Boeing Aerospace Company initiated this study of the Operator-System Interface (OSI) in August of 1984 in response to a need expressed by NASA for study coverage in that area. The study:

- Characterizes an OSI for an extra vehicular (EV) robot system to perform maintenance functions on the Space Station,
- Develops OSI scenarios for that system, and
- Assesses the associated technologies

Dr Victor Anselmo was the NASA manager of the study and the Boeing effort was lead by Paul Meyer of Boeing Aerospace Company, who was supported by Dr. Douglas Dorrough and Ron Hammond of the Boeing Computer Services Artificial Intelligence Center. Other contributors to this report are Joe Hopkins, Henry Lahore, Mark Lawler, Judi Qualy-White, and Amy Toussaint.

Key Words

Space Station
Operator-Systems Interface
EV Robot
Artificial Intelligence
Autonomous

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LIST OF ACRONYMS

AI	Artificial Intelligence	KBS	Knowledge Based System
A&R	Automation and Robotics	MRMS	Mobile Remote
BCS	Boeing Computer Services	MTBF	Manipulator System
CAD	Computer Aided Design	NASA	Mean Time Before Failure
CAMS	Cybernetic		National Aeronautics and
	Anthropomorphic	OMV	Space Administration
	Machine Systems		Orbiting Maneuvering
CMG	Control Moment Gyros	OSI	Vehicle
DARPA	Defense Advanced	RCS	Operator System Interface
	Research Projects	RTSR	Reaction Control System
	Administration		Real Time Systems
DIRECT	Decision Impact Risk	SRI	Research
	Evaluation and Control		Standford Research
	Technique	S/S	Institute
DMS	Data Management	TA	Safety/Sanity
	Systems	TAARGET	Technology Assessment
EV	Extra Vehicular		Transnational Assessment
EVA	Extra Vehicular Activity		of Autonomous Robotic
FOV	field of view		Generational and
GTR	Generic Technology	TV	Evolutionary Technology
	Requirements	TVKC	Television
HUD	Head Up Display		Television Augmented
IBM	International Business	VHSIC	Khatib Control
	Machines		Very High Speed
IC	Integrated Circuit	VICE	Integrated Circuit
IOC	Initial Operational		Voice Intentionally
	Capability	VLSIC	Constrained Evaluator
IV	Inter Vehicular		Very Large Scale
KBIU	Knowledge Based Image		Integrated Circuit
	Understanding		

1.0 INTRODUCTION

This is the final report of a Space Station Automation and Robotics Planning Study, which was a joint project of the Boeing Aerospace Company, Boeing Commercial Airplane Company, and Boeing Computer Services Company. Figure 1-1 shows the work breakdown for the Boeing study tasks. This study is in support of the Advanced Technology Advisory Committee established by NASA in accordance with a mandate by the U S Congress. Our support complements that provided to the NASA-Contractor study team by four aerospace contractors, the Stanford Research Institute (SRI), and the California Space Institute. This study identifies automation and robotics (A&R) technologies that can be advanced by requirements levied by the Space Station program. The methodology used in the study is to establish functional requirements for the operator-system-interface (OSI), establish the technologies needed to meet these requirements, and to forecast the availability of these technologies

Boeing entered the study in the third month of a six month effort to address the OSI issues (sometimes called man-machine interface issues) The other aerospace companies working on this study focused on functional aspects of automation and robotics including subsystem management, space manufacturing, free-flyer servicing and space construction, but none of the contractors were specifically tasked to address the OSI The OSI is integral to the other topics and affects Space Station technology growth considerations as human involvement in Space Station caretaking is replaced by automation and robots The OSI topic chosen for this study is not controls and displays, which are relatively well understood, but rather the advanced automation functions that define these interfaces.

The roll of SRI in the NASA-Contractor group was to provide focused technology forecasts to support the analysis and to guide the system concept design performed by the aerospace contractors. Because contracted tasks were set before Boeing joined the study, the technology support provided by SRI was not available for our part of the study. The Boeing Computer Services (BCS) Artificial Intelligence (AI) Center provided similar support for the OSI topics we addressed. The BCS AI Center is particularly well suited to perform the required technology definition and forecasting tasks because of their connection with studies on similar topics that have been done for other users Figure 1-2 shows a functional organization chart for the BCS AI Center.

Boeing Computer Services (Artificial Intelligence Center)

- **Operator/software interfaces**
 - Speech/Natural Language
 - Voice recognition systems
 - Voice synthesis systems
 - Use of AI
 - Expert systems
 - Machine learning
 - Related AI Technologies
- **Technology forecasting**
 - Availability
 - Holes
 - Required attention
 - Time frame
 - Budget

Boeing Aerospace Company (Space Station A&R task force)

- **Management**
- **Reports**
- **Stationkeeping OSI concepts**
 - Proximity operations
 - External robot
 - Robot OSI
 - Concept description
 - Scenarios
 - System parameters
- **Skylab astronaut experience**
 - Consultation on human side of OSI

Boeing Commercial Airplane Company

- **Consultation**
 - Flight deck designer experience
 - Stationkeeping requirements
 - Interactive controls and displays
 - Test pilot experience
 - Human side of 767/757
 - OSI

Figure 1-1: Work Breakdown Structure

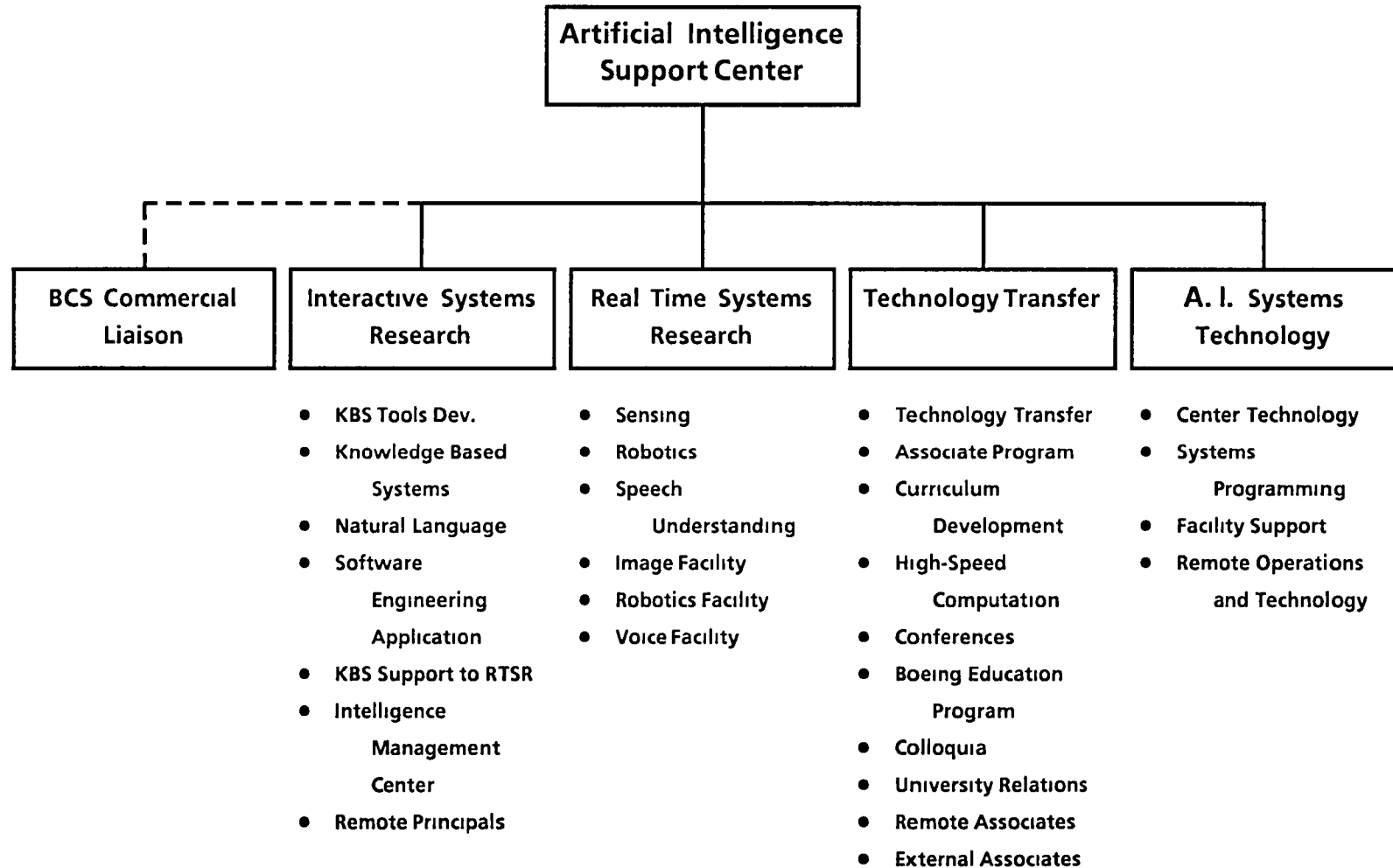


Figure 1-2 AI CENTER FUNCTIONAL ORGANIZATION

1.1 Scope of Study

The overall OSI for the Space Station covers operator interfaces to a wide range of automation and robotics functions, including subsystem management, planning, mission management, maintenance management, logistics management, free-flyer servicing and operation, and proximity operations. Each of these involves the display of monitoring, diagnostic, and advisory information to the crew and the acceptance of planning or discrete command inputs from the crew. The software functions required to generate, interpret, and manage the information, as well as to perform the decision making needed for diagnostic and advisory outputs, will lead to technology advancements. The system characteristics and scenarios that describe those software functions constitute the concept definition output of our study. The technology identifications and forecasts related to those functions are the outputs of our study which support technology planning.

Study schedule and resource limitations required us to focus on a specific aspect of OSI. We selected a topic that drives out advanced software technologies but is credible for Space Station use within 10 to 15 years after the initial operational capability (IOC). As shown in Figure 1-3, our study looked at progressively more detailed Space Station functions, starting from general stationkeeping functions, down to proximity operations, and finally to the extra vehicular (EV) robot functions. The EV robot we envision would be a free-flyer while in transit from one location to another in close proximity to the orbiting Space Station. The OSI would perform path planning, tracking and control, object recognition, fault detection and correction, and plan modifications in connection with EV robot operations. The implementation of the OSI implies the use of natural languages, voice recognition and synthesis, speech understanding, expert diagnostic and advisory knowledge systems, and machine learning. The technologies for these implementations are expected to evolve through three distinct phases, as discussed in Section 4. Figure 1-4 shows a flow diagram indicating how software development could support OSI for an EV robot.

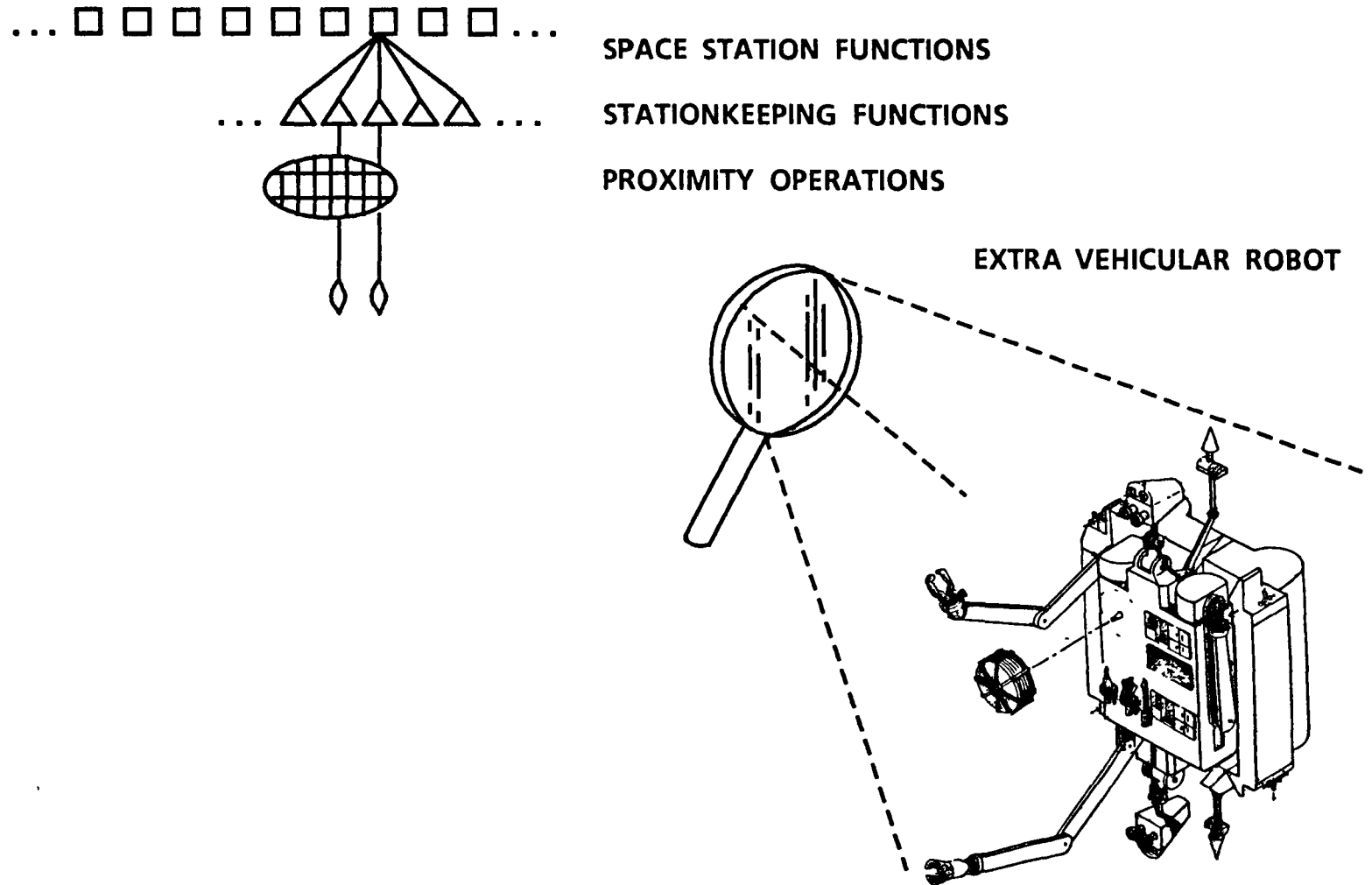


Figure 1-3 AREA OF FOCUS

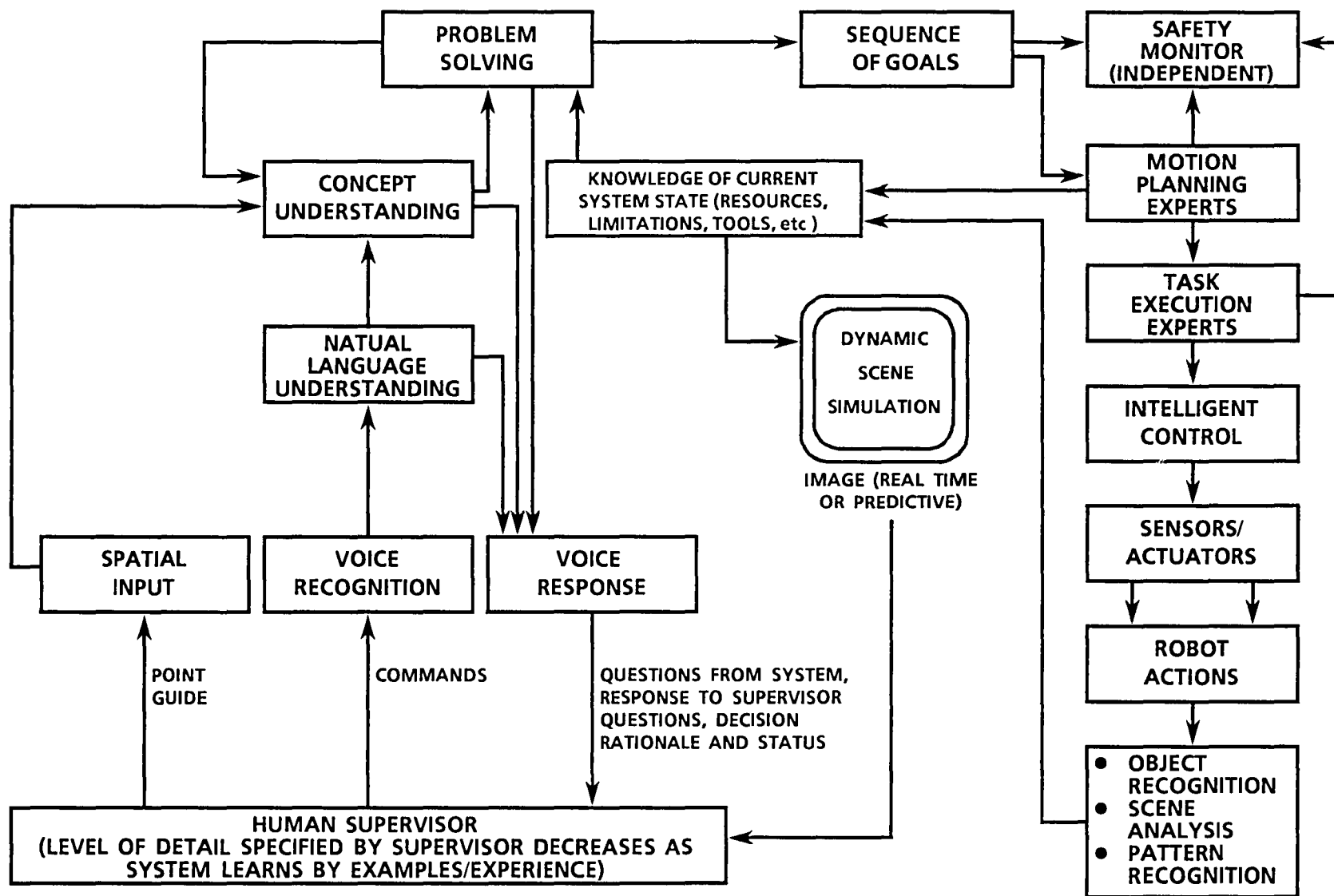


Figure 1-4 SOFTWARE ASPECTS OF OSI FOR ROBOT CONTROL

1.2 DEFINITIONS

The following established definitions have been used in this report and are included here for easy reference.

Automation

Automation is the use of machines to effect control of system/subsystem processes in a predefined or modelled set of circumstances

Artificial Intelligence

AI is the part of computer science concerned with the design and implementation of programs that make complicated decisions, learn or become more adept at making decisions, interact with humans in a way natural to humans, and in general exhibit the characteristics we associate with intelligent human behavior. Intelligence, as used here, is the ability to meet and cope with novel situations by adjusting behavior, the ability to comprehend the interrelationships between facts and concepts, and the ability to generate new concepts and relationships from those already known, i.e., already in a database. Artificial, as used here, indicates that intelligence is achieved by means of a computer or electro-mechanical-optical device.

Autonomy

Autonomy is an attribute of a system/subsystem that will allow it to operate within its specified performance requirements as an independent unit or element without external intervention for a specific period of time.

Expert System

Expert or knowledge based systems are systems that use a significant amount of expert information about a particular domain to solve problems in that domain. The system is able to perform at the level of a human expert in that domain of knowledge.

Knowledge Engineering

This discipline involves with extracting, articulating, and computerizing knowledge. Knowledge engineering addresses the problem of building skilled computer systems by extracting the expert's knowledge and then organizing it in an effective implementation.

Machine Autonomy

Machine autonomy is defined as the ability to function as an independent unit over an extended period of time, while performing a variety of actions and while responding to stimuli produced by integrally contained sensors

Robot

A generic term, connoting many of the following ideas A machine capable of manipulating objects and/or movement having enough internal control, sensing and computer analysis to carry out a more or less sophisticated task. The term usually connotes a certain degree of autonomy and an ability to react appropriately to changing conditions in its environment

Teleoperation

A teleoperated robotic system is one that utilizes cybernetic anthropomorphic machine systems (CAMS) technology in order to permit the human operator to transmit his or her intelligence and dexterity through the machine and to the task All decision-making capability resides with the human controller A servo-control system usually transmits a small proportion of the load force to the operator's hand(s), thus giving him or her "instinctive control" of the job. Frequently, six degrees of freedom are present These include horizontal extension, hoist, azimuth rotation, yaw, pitch, and roll.

1.3 Organization of this Report

This report presents an overview of the study, describes an OSI concept for EV robot operations based on a hypothetical task scenario and astronaut/system interactive dialogue, makes a technology forecast, and sets forth conclusions and recommendations.

2.0 STUDY OVERVIEW

During the second session of the 98th Congress, the appropriations for Space Station funding were established by a House/Senate conference. In their report, the Senators and Representatives on that committee emphasized automation and robotics as part of the Space Station Program, as the following quote from that report illustrates:

The Space Station Program offers an opportunity to stimulate the development of advanced technologies in the fields of automation and robotics. To this end, the conferees adopted the Senate provision establishing an Advanced Technology Advisory Committee mandated to identify specific Space Station systems which advance those technologies that are not in use in existing spacecraft. Examples of such technologies include advanced vision sensors, computers that can serve as expert systems, and manipulator systems with advanced multiple degrees of freedom. The conferees intend that, where appropriate, the Committee may as a secondary task also identify systems currently in use whose potential for enhancing automation and robotics technologies appears promising. The conferees both intend and expect that the technologies of Space Station automation and robotics will be identified and developed not only to increase the efficiency of the station itself but also to enhance the Nation's technical and scientific base leading to more productive industries here on earth.

In response to this directive, NASA established an Aerospace Contractor Study Group to cover four specific areas of automation and robotics application to the Space Station.

Satellite Servicing	- TRW
Space Manufacturing	- General Electric
Space Assembly and Construction	- Martin Marietta
Subsystems Management	- Hughes

Initially Boeing was not a participant, but offered to assist the NASA effort by studying the impact of the operator-systems interface on Space Station automation. Boeing has

significant experience in that area as part of the advanced commercial airliner flight deck development. The following is a list of some significant features of the OSI approach to 757/767 flight deck design

- Integrated digital instrumentation
- Flight deck commonality
- Simplified procedures
- Increased automation/decreased workload
- Consistent caution/warning philosophy
- Optimized crew size and accommodations
- Advanced human engineering design methodology
 - Extensive pilot and customer participation
 - Work load assessment
 - Extensive engineering simulation
- Quiet, dark cockpit

OSI is the system of hardware and software that facilitates communication between human operators and the hardware/software system that monitors and controls a functional system. On the Space Station, the functional systems that will be controlled and monitored will include those involved with housekeeping, stationkeeping, and mission and operations planning and scheduling. The following lists these functions and some of their sub-functions:

- Housekeeping
 - Subsystem management
 - Inventory control
 - Resource management
 - Inspection and maintenance
- Stationkeeping
 - Orbital maintenance
 - Space Station and free-flyer formation control
 - Free flyers approach control
 - Proximity operations (manipulators/EVA)
 - Momentum management
- Planning and Scheduling
 - Tasks

- Logistics
- Mission

All of these could be supported by the OSI to provide the on-board astronauts with a display of status, control, and advisory information, as well as a means of giving directives to the functions. The OSI would include software that resides in the Space Station data management computers or in special-purpose processors associated with a particular function. The software would support OSI input/output functions such as speech recognition or multifunction display processing and it could support the diagnostics and simulation processing that feeds information to the displays. Space Station constraints on OSI are shown by Figure 2-1.

The human factors aspects of OSI design lead to the general requirements listed below.

- The OSI shall be "user-friendly" and to implement that the OSI shall:
 - Provide feedback to the operator
 - Provide appropriate level of detail
 - Allow different ways for operator interaction
- The OSI shall be multifunctional to minimize power, weight, and volume and to reduce operator workload and error rate
- Information integration shall be used to reduce workload and error rate
- Commonality in format and operation shall be maintained.

As stated in Section 1.0, this study focused on one aspect of the OSI. The EV robot function was selected because it represents a forward-looking application of automation and robotics and because of these additional factors:

- The function identifies across-the-board OSI technology needs
- It can be implemented without risking Space Station schedule or cost goals
- It is within the OSI area and does not duplicate the work of pre-existing contractors
- The technology is generic to many potential Space Station applications
- The technology is applicable to Earth-based applications and will increase U.S. technical competitiveness.

- VARIETY OF MISSIONS AND MODULES REQUIRES VERSATILITY

- ZERO - G ENVIRONMENT



- POSTURAL CHANGES
- LINE - OF - SIGHT FALLS 25 DEGREES BELOW HORIZONTAL REFERENCE
- HEIGHT INCREASE
- NORMAL OPERATING POSITION IS NOT SEATED
- POSSIBLE CHANGES IN QUALITY OF VISION

- DIVERSE BACKGROUNDS OF CREW MEMBERS
- CREW MEMBERS NOT HIGHLY TRAINED IN ALL AREAS
- CREW MEMBERS ATTENTION MAY BE DIVIDED AMONG MULTIPLE TASKS

Figure 2-1 SPACE STATION ASPECTS OF OSI

The principle method used in this study to characterize the use of OSI for an EV robot is the scenario of a day's operations by the robot and the associated operator interactions. Section 3.2 present the robot task scenario and an astronaut/system dialogueue that illustrates a specific OSI interaction with an astronaut.

The EV robot system is envisioned to be a free-flying vehicle that will operate outside the Space Station. The robot will be equipped with manipulator arms to hold itself to a work site and to perform physical tasks at a work site. The vehicle would be plugged into a specific berthing port on the outside of the station while being programmed and

recharged with expendables. It would be deployed from that port and travel by its own propulsion system near the Space Station to perform its assigned tasks. The primary advantage of the EV robot system is that it would increase crew productivity by reducing the amount of time required for EVA on routine and frequently-occurring tasks and by performing tasks that exceed human capability. It would also reduce risks to the crew by performing hazardous functions. Figure 2-2 depicts one robot design concept and figure 2-3 illustrates a simple sequence of tasks that could be executed by an EV robot.

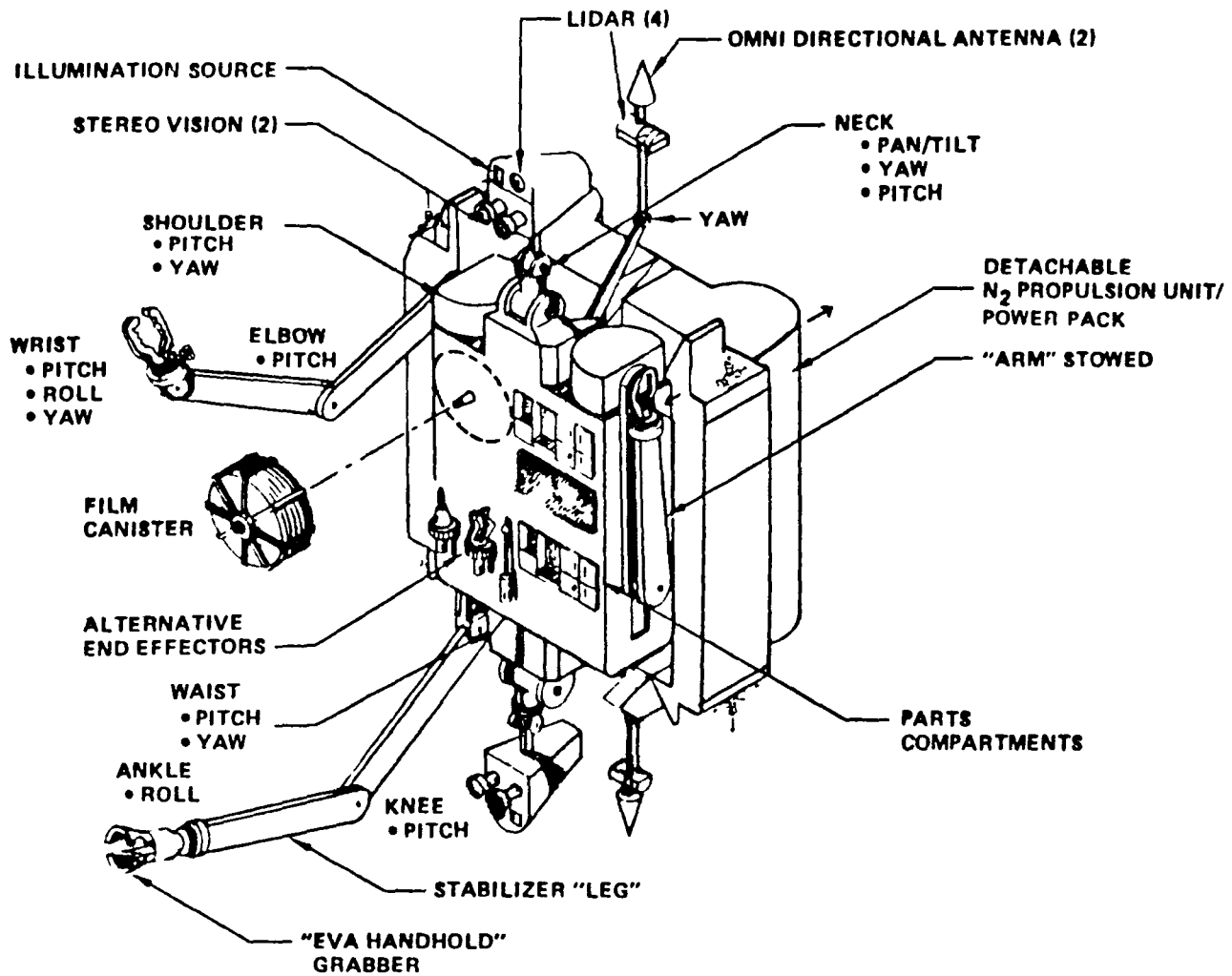


Figure 2-2 AN EXTERNAL ROBOT CONCEPT

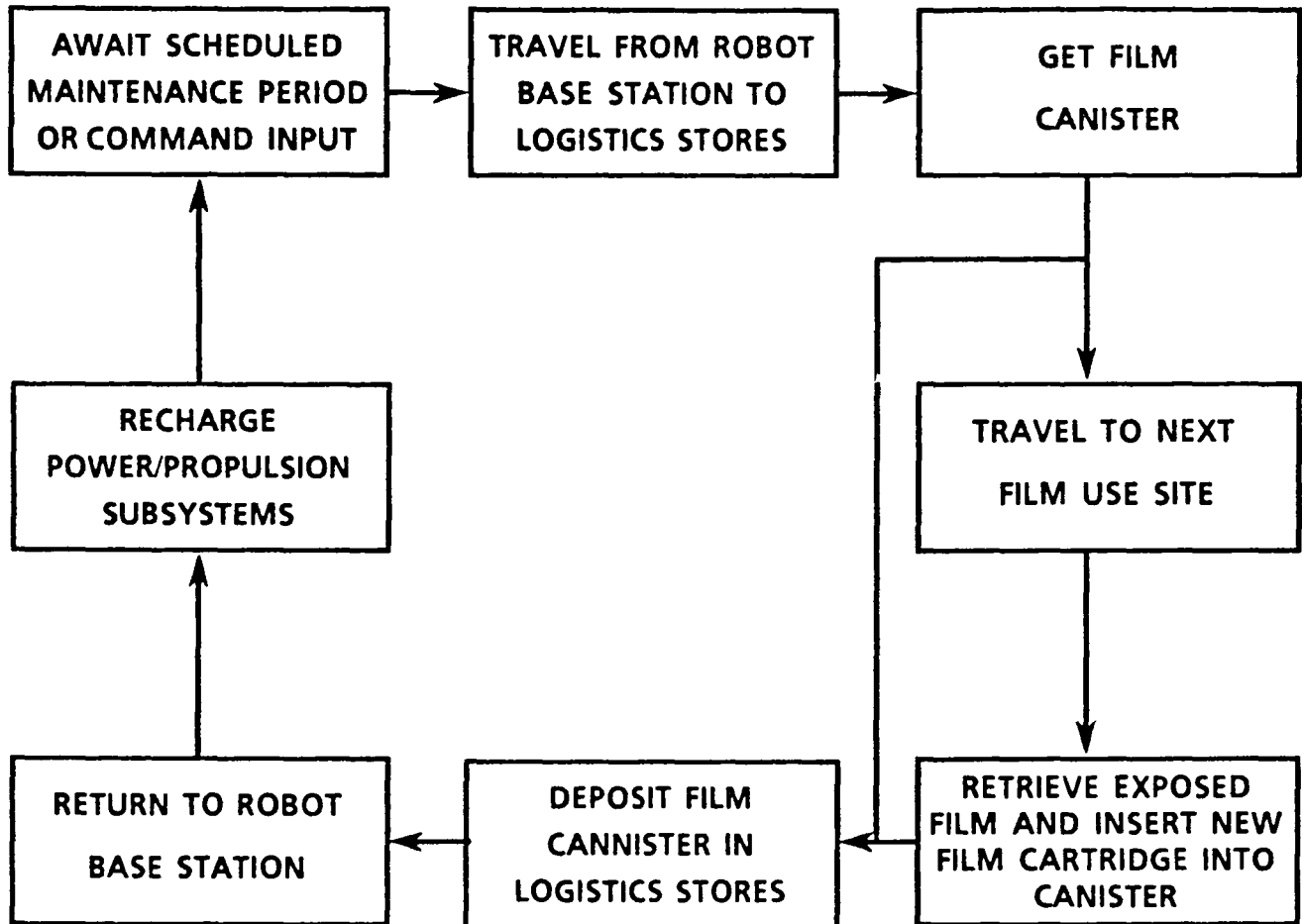


Figure 2-3 EV ROBOT TASK FLOW

This report focuses on the OSI supervisory mode of directing a robot. The scenarios in Section 3.2 were selected to drive out many generally applicable AI technologies. Some of the technologies indicated by the scenarios and dialogue of Section 3.2 include:

- voice recognition
- speech understanding
- natural language understanding
- machine reasoning
- image understanding

adaptive data base management
expert systems
learning systems

The scenario given in Section 3.2.1 indicates the range of tasks that an EV robot could perform to support Space Station maintenance, experiment, and astronaut EVA operations. The dialogue in Section 3.2.2 describes an interactive OSI session during which an astronaut provides directions for completing a robotic task. This task, which modifies a similar task, requires the addition of some procedures developed during an experimental program.

This instruction session is conducted by the astronaut in a work station in the Space Station. The astronaut is interacting with a software program within the Space Station computer system. This instruction program and simulation will be of a fidelity that, once the task is demonstrated to be understood, the instructions can be stored, appropriately assembled with other tasks, and downloaded to an EV robot prior to the time the task is to be performed.

When the robot leaves its berthing area it will have a schedule of tasks to perform, a travel path calculated to reach the task sites; a 3-D map of the static Space Station; and the intelligence to perform some deviations from the preprogrammed plan. For example, it will have sensors and communication means which will keep it informed of its location and other objects moving in the proximity of the Space Station. The robot will be provided with collision avoidance procedures which will permit some plan deviation and still maintain autonomous operation. As the EV robot performs its tasks it will be able to report to and receive commands from the astronauts and the Space Station computers.

One of the most significant considerations in defining this OSI concept is the use of astronaut time. The OSI must accept high-level, verbal and graphics instructions that can be input by the astronaut quickly and simply. Another consideration is the variation that would be inherent in each astronaut's delivery of high-level directions. The OSI would need to have a natural language capability adaptable to all of the anticipated human users.

Section 4.0 of this report gives a technology assessment that was performed by the BCS AI center. The assessment presents an evolutionary sequence for the development of A&R

technologies from the present to about 2010. The concepts described in Section 3.2 would fall into the Phase 3 of the assessment, as discussed in Section 4.2.3.

The question of teleoperation versus autonomous robot evolution has been raised and is discussed in some detail by Section 4.4.

The conclusions resulting from this study and a recommendation for an OSI advanced development program are included in Section 5.0.

3.0 DESCRIPTION OF THE OSI FOR AN EV ROBOT

This Section describes the tasks that would be performed by a mature EV robot system; tasks that represent a significant pull on AI and robotic technology. These tasks are illustrated by two scenarios, one describing a full day's work by an EV robot and the other describing a task planning dialogue between an astronaut and the OSI. These scenarios are followed by a description of some of the operational requirements for an EV robot/OSI system, including OSI communication functions, task planning and scheduling, and anomaly management

3.1 Critical and Routine Tasks

The reasons for using robots on the Space Station are to relieve the crew of time-consuming, potentially hazardous, and highly repetitive tasks. The critical tasks to be performed by an EV robot, such as handling hazardous materials, performing extended EVA operations and assisting with superhuman precision adjustments, are the design drivers exerting the most technology pull on the OSI system

In addition to critical tasks, the EV robots can be expected to perform tasks that are day-to-day, predictable, well-defined, and repetitive housekeeping chores. These tasks, which include inspecting the Space Station exterior for damage or wear and removing contamination from exterior surfaces, do not represent an optimal use of crew time when performed through EVA. The unproductive "overhead" time required to suit up, gather materials, travel to and from the task site, and unsuit after the task is done, may well overwhelm the time required for the task itself.

Another set of routine tasks well within the postulated capability of EV robots is experiment support. Many instruments used in space experiments will require routine servicing such as replenishing consumables, replacing focal plane instruments, changing film cannisters or optical filters, and placing or retrieving material samples. While similar in required capability to the housekeeping tasks, these tasks are not as basic to EV robot services because they are not as routine. That is, the task requirements will change from experiment to experiment and the planning and robot programming for the task will probably have to be done on-station. Therefore, the savings in crew time are not as great as for automating housekeeping functions. These tasks will also depend on the existence of Space-Station-deployable, task-oriented planning software for the EV robots.

In addition to performing critical and routine tasks, EV robots may also be able to serve as crew assistants. A mature EV robot could be used as an assistant to a human crew member in addition to performing tasks autonomously. These capabilities could reduce the frequency or duration of EVA or reduce the number of crew members needed for some EVA tasks. One of the simpler crew support applications, which may be possible with a rudimentary EV robot system, is to use a robot to provide a remote view of a potential EVA site. The Space Shuttle has used a TV camera mounted on the remote manipulator for a similar application. A robot carrying a TV camera or other sensor could be dispatched to provide crew visibility of a remote site to aid in EVA planning. The robot could also continue surveillance during EVA as a sensor for the crew member(s) monitoring the EVA. In a more sophisticated assistant application, the EV robot could act as a caddy, tagging after the EVA crew member, carrying and fetching tools and materials. The highest level of assistant task is for the EV robot to act as an extra set of hands in positioning tools and materials and to lend strength or precision to the crew member.

The OSI between the EV robot and Space Station crew will evolve as robotics tasks become more complex. The OSI features that will be needed frequently, such as the communication functions discussed in the next Section, must be at the crew's fingertips and not just at a centralized command and control station. If a crew member must travel to a central console to issue frequent commands to a robot performing routine tasks, the time-savings of using the robot may be lost. Therefore, a portable remote communications system will be required. As the robot technology becomes more autonomous, the frequency of communication will probably decrease. The third level of tasks described above will require a natural language interface to on-line task planning and control. Such capabilities will certainly not be available when the EV robot system is used initially and will provide a significant technology pull on AI and robotics.

3.2 Scenarios

The following two scenarios illustrate how a robot might perform some of the types of Space Station-related tasks described previously. The first scenario summarizes a range of tasks that could be performed during one day, and the second scenario illustrates an OSI sequence between a crew member and the task planner for a relatively autonomous robot. These scenarios were created to establish an innovative idea envelope within which the conceptual designs could be developed and to which the forecasts for technologies

necessary to support an EV robot OSI development could be addressed. The events are extrapolated from what could be possible, based on the current state of the art, by about 2000 to 2010.

3.2.1 Full Day Scenario

This scenario is presented to indicate the range of tasks that an EV robot might perform for the Space Station. It provides the setting for our OSI concept definition.

One morning after a busy night of tasks, the task planner (computer) creates a schedule of tasks for the robot, which are derived from the following requirements list

- A sensory experiment requires a bad card changeout - URGENT
- An observation experiment requires a film pack change.
- Two experiments require battery pack changeout
- Two experiments require routine calibration
- One experiment has mounting problems - needs examination - astronauts had requested further examination from previous day
- One astronaut requests 1.5 hours of robot time to assist in EVA task from 0930 - 1100
- Internal preventive maintenance period must be conducted.

The schedule created leads to the following events

- 0700 -- Robot performs routine self-check tests (replaces one joint servo that isn't within tolerance - logs change)
- 0730 -- Robot loads up with propulsion pack, 1 film cannister, 2 battery packs, 1 computer card, calibration test equipment
- 0750. -- Robot moves toward first task (begins sensor observation of exterior while in transit). During observation notes 3 configuration differences - places message for astronaut review
- 0810. -- Arrives at sensor experiment - replaces bad card
- 0825. -- Selects path to next task. Begins movement toward next task (starts sensor observation of exterior). Notes 2 anomalies. Expert system determines 4 of

the 5 anomalies found so far are near the damaged sensor which was just repaired Initiates low-level annunciation signal for astronaut alert.

- 0836: -- Arrives at experiment - changes battery pack.
- 0844: -- Selects path to next task. Moves toward next package (because of proximity to current location, no exterior observation).
- 0850: -- Arrives at experiment, Earth observation camera E16B - changes film.
- 0915: -- Robot moves to airlock to load up with tools required for EVA assistance task, places exposed film in airlock for astronaut attention, and changes out propulsion/power pack.
- 0930: -- Robot arrives with astronaut at EVA operations site
Another robot joins task to perform 'gofer' functions
- 0950: -- Robot provides spotlight illumination for astronaut as Sun sets
- 1025: -- Robot senses sunrise and turns off spotlight.
- 1100: -- EVA task ends. Astronaut interrupts schedule - asks robot to return to area of damaged sensor (repaired earlier). Robot performs detailed inspection under direction of two astronauts It appears that a micrometeorite may have caused damage. Astronauts decide to perform EVA at 1300 to further examine area and select any necessary repair options. The robot's presence is requested, which causes the task planner to update the schedule.
- 1145: -- Robot selects path to nearest task (turns on observation sensors while traversing - no discrepancies noted).
- 1153: -- Arrives at experiment - performs calibrations.
- 1217: -- Selects path to next task - observes exterior while traveling.
- 1226: -- Changes batteries on experiment
- 1229: -- Selects path - warned of OMV approach in proximity of task - waits for completion of OMV docking
- 1247: -- Moves off to next task - observes exterior
- 1308: -- Arrives late at EVA inspection site Had been monitoring astronaut progress, but calibration had taken longer than planned, and astronaut had arrived earlier than projected - error noted for further scheduling considerations.
- 1344: -- Astronauts decide repair will be performed later in week after more time has been given to assessing and preparing repair options

At this point, there are no other immediate tasks for the robot to perform or assist on. However, the task planner has a number of functions stored that are either standard

servicing requirements that need to be integrated into the robot's schedule or are new requests that were issued when the robot was occupied but that didn't require an interruption because there was no specified time. The following is a list of these outstanding requests, which is followed by a task scenario that shows how they are integrated into the next segment of the robot's schedule.

New requests

- Assist a crew member in positioning an experiment package. MRMS will also be used. Robot to provide additional eyepoint
- Clean exterior surface of Window C within the next 36 hours to accommodate an Earth-observation photo session from station interior. Location of smudge on window noted.

Unscheduled maintenance/support tasks

- Perform preventative maintenance on 2 experiments based on trend failure analysis
- Repair a piece of hardware on the solar arrays based on analysis indicating excessive degradation
- Complete an instrument calibration based on projections of a busy schedule when the normal calibration would occur.
- Survey sector 3D-2 sub 6. This is required because no recent activity has occurred in this vicinity.

1345: -- Robot moves to home lock area
 1353: -- Unloads equipment used on prior tasks and switches out power packs Loads up with maintenance tools.
 1403: -- Moves to first experiment site.
 1412: -- Begins maintenance (cleaning, adjustment, replacement).
 1435 -- Moves to 'early' instrument calibration via sector 3D-2 sub 6. Performs exterior survey during traverse.
 1457: -- Performs calibration of instrument package
 1503: -- Receives message that astronaut-assist task will begin at 1530
 1509: -- Moves to site of astronaut-assist task.

- 1518. -- Arrives at site early. Notifies crew of arrival, goes into background mode while awaiting task start.
- 1530. -- Provides mobile "flying" eyepoint for MRMS maneuvering. This mobility is directed by natural language/communication techniques.
- 1610. -- Robot switches on spotlight to provide illumination.
- 1623. -- Task completed. Returns to home lock area for window cleaning equipment.
- 1637. -- Unloads equipment, picks up cleaning tools.
- 1648. -- Moves to window.
- 1701. -- Cleans window. Astronaut happens to be in area and sees task. Interactively suggests additional spots on window that need attention.
- 1743. -- Moves to next task.
- 1754. -- Performs routine preventative maintenance task.
- 1827. -- Returns to home lock.
- 1841. -- Unloads equipment. Selects tools for solar array repair.
- 1852. -- Moves to spares storage lock area.
- 1908. -- Collects array parts that will be replaced.
- 1923. -- Moves to solar array area requiring attention. Reduces speed when near array to reduce danger of collision and minimize contamination; continually senses array location as it rotates.
- 2003. -- Begins repair of structure.
- 2121. -- Moves to Scientific Airlock #2L (Large).
- 2139. -- Unloads degraded struts and mirrors (for later analysis by crew).
- 2153. -- Moves to home lock.
- 2204. -- Plugs self in. Nothing urgent on schedule, performs internal checks.
- 2217. -- Task-planner schedules next series of tasks from low-priority lists. Notes restriction that crew will be bedding down for night shortly and that the habitat module will be off-limits for outside maintenance.

3.2.2 Operator/System Dialogue

The first scenario showed the types of EVA a highly developed robot could perform to support the Space Station crew. Based on that kind of support function, the following script represents an OSI "dialogue" between the EV robot system and astronaut that shows how the OSI instructions are conveyed.

Let's examine in some detail how the robot task planner is directed to program a change to the task listed at 0850 in the first scenerio. The astronauts are installing a new camera to perform Earth-sensing photography. Before the camera becomes operational, a member of the crew must conduct a dialogue with the software that develops task plans for the robot. This software, which will be contained in the Space Station's computing and data management system, would have access to a CAD database describing the station and its equipment. It would also have access to existing robot task plans and to simulation and graphics software.

The result of the dialogue between the crew member and task planning software would be a new set of instructions for an EV robot. These instructions would have been developed and verified cooperatively by software and the astronaut and demonstrated by simulation. A crew member would probably observe the first execution of the new task to further verify the task plan. The dialogue would be along these lines:

Astronaut	"Hello, Task Planner."
Audio	"Task Planner here."
Astronaut	"We need a new film cannister exchange program at this location; computer graphics please "
Computer Display	(CAD solids model version of Space Station is brought up)
Astronaut	Rotates and frames display to show robot's berth and the location of the work site
Astronaut	"Note the location" -- points to the work site location with pointing device.
Audio	"OK."
Astronaut	"The cannister is for the E16C camera, which is like the old E16B; computer comparison graphics please."
Computer Display	(Color coded CAD solids models of the E16C and E16B cameras are overlaid).
Astronaut	"Note that the door is shaped differently please;" rotates the display simultaneously
Audio	"OK."
Astronaut	"The latch mechanism operation is different, note please," points to latch mechanisms with pointing device.
Audio	"Show me."

Astronaut	"The new latch is the same as the experimental version we used on test 0178-V3 computer, run simulation with graphics please, Task Planner, note please "
Computer	(Runs simulation of the operation of the latch mechanism and displays the sequence).
Audio	"OK."
Astronaut	"The work site area is the same as before."
Audio	"OK."
Astronaut	"The photography schedule is the same as the G33A we ran for the E16B "
Audio	"Start date?"
Astronaut	"Day after tomorrow "
Audio	"OK."
Astronaut	"Notify me when each exposed film cannister is ready please "
Audio	"OK."
Astronaut	"Play that back please "
Computers	(Runs simulation of task displays travel, task; elements, and schedule)
Astronaut	"Looks OK, store please "
Audio	"Task Planner, OK and out."

3.3 OPERATOR - SYSTEMS INTERFACE

The dialogue presented in Section 3.2.2 describes an OSI that uses several advanced technologies. This Section discusses each of those technologies from a functional point of view. The OSI system that is implied in the discussion includes an internal robotic computer and embedded software, a centralized Space Station computer (task planner or scheduler), and related, supporting functions of the onboard Space Station data management system.

3.3.1 Communication Functions

The operational philosophy for the OSI will be to provide a natural communication link between astronauts and the onboard computer system including the robot. For the astronauts, natural communication means input of data and commands using methods such as speaking and pointing, and receiving feedback through visual and aural channels. To the computer and its associated peripherals, natural communication implies the necessary hardware and software required to accept from and express data to the astronauts in a lucid manner; indeed, the hardware and software should be transparent (i.e., unambiguous) to the user. The astronaut should not be required to learn a new language or rigid command syntax rules.

The dialogue given in Section 3.2.2 represents an OSI concept that uses this natural communication philosophy. The conceptual design described below delineates the components and operational requirements of each OSI element. However, the description does not include component layout, OSI geometry, or hardware specifications. The components envisioned for this OSI include color graphic displays, voice recognition and synthesis, and nonverbal communication links (keyboard, hand controller, and touch input device).

3.3.1.1 Displays

Pictorial and graphics displays will be the primary method for presenting visual data to Space Station crew members, although some control operations may require direct viewing. These displays must integrate data into an easily comprehensible format to help the operator understand and act on the data presented. Studies have shown that 90% of the information we process is received through visual data, most of which is perceived as

objects, not words or numbers. Therefore, the displays will present mostly dynamic or static pictorial graphics presented in real time, which will be supplemented by alphanumeric data. The displays may be presented on a large flat screen (as opposed to a CRT) at a central control station and on smaller portable screens that will be part of the remote, possibly hand-held OSI communication link.

There are two OSI display concepts -- head-up (HUD) and holographic displays -- that would not be required for the dialogue presented in Section 3.2.2 but should be studied in more detail. A head-up display (HUD) is an instrument that projects computer-generated dynamic symbology onto a clear combining surface mounted in the operator's field of view (FOV), thereby overlaying the symbology on the viewed scene. The operator then can have all necessary information in the immediate FOV, decreasing eye accommodation and attention diversion problems. A head-up display could be used for both IV and EV activities.

A holographic display presents a true three-dimensional representation of an object or situation to the viewer. This type of display would be useful for flight operations, to simulate a repair task, as a teaching/learning aid, and to evaluate construction techniques. This technology requires some pushing and direction for this application. The specific areas of concern in using holographic displays include power consumption, processing time, and real-time processing techniques.

3.3.1.2 Voice Recognition and Synthesis

The voice recognition system will be used to send commands to the computer and robot. It will provide the astronaut with a natural means of communication - the spoken word. The same commands could also be entered through a keyboard or touch input device. To truly meet the natural communication requirement, the recognition system will have to accommodate a flexible syntax for messages from the crew, although conventional rules of grammar will be observed. The system must also recognize continuous speech, allowing recognizable words or phrases to be spoken at a natural rate. The system will be designed to recognize a speaker by requesting the speaker to recite selected phrases which are recorded by the system. The recordings will then be analyzed for speaker-unique pronunciation of the phonemes included in the selected phrases and these phonemes will be compared to the standard phoneme database whenever the speaker issues a command.

The comparison will allow the system to interpret the speaker's command. This technique minimizes the expenditure of crew time for both system training and use.

The recognition system must also be speaker-independent and speaker-adaptive. Speaker-independent means that the system will recognize a large number of speakers without losing accuracy. However, a speaker will be required to identify him or herself for recognition and security purposes when first using the system. Speaker-adaptive means that the system is flexible enough to recognize a speaker during various stress levels of the speaker's voice.

As the dialogue showed, the astronaut gains entry into the task planning mode for the robot by simply saying, "Hello, Task Planner." This indicates that the OSI recognizes the astronaut's voice and determines that the astronaut is a valid person to give task direction to the robot. The astronaut speaks conversationally and, in fact, doesn't use the most quantitative speech possible: he says "day after tomorrow" for the start date, rather than a specific date. The OSI system correctly interprets the input, employing what it "knows" about that particular astronaut's use of the language so that the "day after tomorrow" is in Earth calendar days, corresponding to the astronaut's sleep-wake cycle.

A voice synthesis system is a natural communication means between the computer and robot, and the crew. Using voice synthesis as a feedback to the crews offloads their already overloaded visual channel and increases the usage of the traditionally underloaded aural channel. To allow the greatest flexibility, the synthesis system will also be phoneme-based. The system will create words by using the phonemes in the database. In addition, the voice-type, (i.e., male/female, accent) will be selectable by the crew.

The OSI system synthesizes audio responses which may, as shown in the dialogue, initially be somewhat structured. As the system progresses, the audio responses would preferably be unstructured and, in fact, be intentionally changed to indicate real understanding of the directions received.

3.3.1.3 Data Display and Exchange

The astronaut and robot/OSI system simultaneously evaluate CAD data. The computer system, on voice command from the astronaut, brings up the designated CAD data for display. In reaction to inputs from the astronaut through advanced input devices (i.e.,

light pens, display pressure point application, etc.), the computer manipulates the CAD data. The OSI "observes" the data in real time and reacts to the astronaut's "Note the location", as the astronaut indicates the displayed location with a pointing device.

To show comparisons graphically, the computer presents data for color-keyed displays with overlays and the system is able to interpret the distinctions in real time. The OSI is also able to distinguish, in near real time, where things are the same or different by reviewing the data presented as the astronaut observes and manipulates the graphic display.

The computer system runs a simulation of sequences selected by voice input from the astronaut and simultaneously displays the results graphically. The OSI system receives the data from the simulation as it is run and displays and interprets that data to identify features needed for the robot's task description. The OSI determines if the data is complete and consistent with the rest of the task description for an "OK" conclusion about the input.

3.3.2 ROBOT TASK PLANNING AND SCHEDULING

The tasks that will be performed by the robot on orbit will be sequenced, integrated, and prioritized by the computerized task planner, in conjunction with commands issued by the crew through the OSI. For example as we indicated in the first scenario, the mature robot will be able to function fairly autonomously in response to a preset schedule of tasks, in addition to being able to integrate unscheduled, routine tasks and emergencies. This task planning capability will be preceded by simulation to assimilate the time, logistics, and procedural elements of the subtasks, which will be modified and updated as they are performed on orbit. The task planner, or scheduler, will receive inputs continuously from the crew and other computers, which will impose new requirements and constraints on the existing schedule. Tasks that require immediate action will interrupt the existing sequence of events. Each task input will have to take into account the completion time needed, paths of travel between tasks, and the resources that will be required to fulfill a task or schedule sequence (tools, power, fuel, parts).

The task planner will also have to integrate information on other objects (Orbiter, OMV, OTV or free-flyers) maneuvering in the proximity of the Space Station or task area, in addition to any environmental constraints such as radiation emissions, signal blockages,

potential contamination sources (such as a thruster firing), and possible crew sleep disturbances.

The robot will perform its scheduled list of tasks either autonomously, checking for updates and changes after completing each task unless interrupted, or it may be involved in a direct astronaut/robot cooperative function, responding to immediate requirements as discussed in Section 3.1.

The popular definition of intelligence includes the ability of an entity to learn from experience and avoid making any drastic mistakes. It is doubtful that a Space Station robot will be given full autonomy until it has such "intelligence." Confidence in the robot's "knowledge" will be gained by simulating many situations, including those in which an operator purposefully makes errors. A safety and sanity (S/S) monitor program should be developed concurrently with other robotic programs. This S/S monitor must have the ability to extract rules to cover similar future situations either directly by observation or, more likely, by means of interviews and conversations with operators.

3.3.3 ANOMALY MANAGEMENT

While the robot may have increasing autonomy as crew confidence mounts and technology advances, there must still be a means for alerting the crew of faults and anomalous situations when they occur. An effective crew alerting philosophy should meet the following two general objectives:

1. Minimize the time required for the crew to detect and assess failure conditions and to initiate correction actions, and
2. Conform to the quiet, dark OSI concept when all systems are operating normally.

Faults and anomalies should be categorized by the safety/sanity monitor into four major classes, each class eliciting a predefined alerting scheme. The first class is information/maintenance data, which include system trend data, maintenance log, etc and do not require immediate crew action or awareness. No aural tone is elicited but a discrete indication (green/white) is given visually, (as shown in Section 3.2.1 at 0750). This data can also be recalled by the crew. The next class is advisory data, which include

operational or system conditions, that require crew awareness and may require subsequent or future crew action. A prominent alphanumeric display (unique color) describing the advisory is provided, as well as a unique aural sound (see Section 3.2.1 at 0825). The third class is caution data, which include abnormal operational or system conditions that require immediate crew awareness and subsequent corrective or compensatory crew action. A master visual (amber) indication, a prominent alphanumeric readout (amber), and a unique aural sound and voice message are issued. The last class is warning data, including emergency operational or system conditions, that require immediate corrective or compensatory action by the crew. This includes all time-critical faults. A master visual (red) indication, a prominent alphanumeric readout (red), and a unique aural sound plus voice message are elicited. These four classes are broad enough to encompass any foreseeable fault or anomaly, and provide consistent nonconfiguring crew-alerting procedures.

As mentioned earlier, the safety/sanity monitor would categorize the faults. In addition, the monitor would prioritize detected faults, implement a safe and hold logic for critical situations, and broadcast a message for the fault to alert the system. The monitor reduces the number of crew alerts by solving minor faults and anomalies and thereby generally off-loads the crew and increases their confidence in autonomous system operations.

Another area of anomaly management involves situations during which a robot has difficulty with a prescribed procedure, or finds that a piece of hardware at a work site differs from that expected. To some extent, a hierarchy similar to the alerting scheme can be followed in these situations. For any situation involving a life-threatening or time-critical task the crew should be notified immediately. Simultaneously, the robot system searches its own memory for a solution. If the situation is not life-threatening or time-critical, the robot should eventually be sophisticated enough to search for a solution autonomously and, only after exhausting potential solutions, notify the crew. The solution search process would involve the safety/sanity monitor as well as the robot's memory.

4.0 TECHNOLOGY ASSESSMENT

Section 3.0 described the capabilities of the OSI that would support a fully autonomous EV robot system. This section begins by describing the technology assessment used to examine the feasibility of this OSI. Section 4.2 then uses the description of section 3.0 and results of the technology assessment to develop a three phase approach to EV robot autonomy. The technology advances required by each of these phases define the technology pull imposed by the Space Station EV robot OSI. Section 4.3 compares the technology pull defined in section 4.2 to estimates of technology availability to define the technology push that must be applied to develop the EV robot OSI. Section 4.4 discusses an alternative evolutionary path for the EV robot, that of building on current teleoperated robot technology, and concludes that a path based on partial autonomy is more likely to lead to a successful EV robot development.

4.1 Technology Assessment: Project TAARGET

Technology can be defined as a set of pragmatic principles, processes, and techniques derived by humans and intended for the manipulation and/or control of physical reality, including the reality of human-produced objects. As defined, it is clear that technology is a pragmatic discipline or methodical effort, but not the results of such effort. Thus, structures, tools, machines, or any other artificial object is an artifact of technology, but not technology itself. However, artifacts can be used to estimate the status of the development of technology, thereby forming the basis for technology assessments.

A technology assessment (TA) is a set of statements and associated illustrations that describe the current and/or projected development status of a particular set of pragmatic principles, processes, and techniques by using the artifacts of same. A comprehensive TA requires an examination of current literature, consultation with experts in the technical area being assessed, and sophisticated forecasting and statistical methods to infer the future of the technology. Fortunately, a recent, full-scale assessment of robotic technology was available to support this study. Boeing used the Transnational Assessment of Autonomous Robotic Generational and Evolutionary Technology, (TAARGET), as a source of technology assessment for two reasons: because time constraints did not permit an independent, company-sponsored, effort; and the perceived excellence of the TAARGET effort itself.

Project target is described in Section 4.1 2

4.1.1 Factors Influencing Technology Development -- Push and Pull

The direction of a given technology is largely controlled by technology pull; that is, by operational and/or systems requirements the fulfillment of which necessitate the generation/development of relevant technical disciplines, products and processes.

Technology pull starts with a set of operational requirements that serve as a necessary, but not a sufficient, condition for developing new technology. These requirements are usually generated by the "customer" (e.g., government agency, industry, organization, individual, etc.) and are usually a set of generic operations that a system will be expected to perform and against which it will be ultimately tested. Each one of these operational requirements must be translated into a detailed set of functions to be performed by any specific system expected to meet the operational requirements. These functions are known as functional requirements. They are independent of specific technologies in that more than one basic technology could be made to perform the functions dictated by the set (e.g., discrete vs integrated circuits).

The next step translates functional requirements into a set of generic technology requirements (GTR). These may or may not be specific-technology independent. They are "clusters" of interrelated technologies that can be used to perform major subsystem functions (e.g., the inertial measurement unit or the guidance computer in a spacecraft or ballistic missile).

The final step is very technology specific. Where possible, it identifies specific techniques and processes that are mature enough for immediate support of the previously identified GTR's, functional, and operational requirements. It may also identify techniques or processes that are not mature enough to meet these requirements. In that case, the requirements are said to "pull" the as-yet immature technology.

Obviously, technology pull is a polar concept that must be considered in relation to its opposite, technology "push", those relevant technical and/or socioeconomic events that affect the arrival (maturing) time of a new technique or process. Socioeconomic events are usually characterized by,

- 1) Generation dynamics: the elapsed time between one generation of a particular technology and the next
- 2) Technology transfer time: the elapsed time between one major area of application and the next

Both can be accelerated or decelerated by political and/or economic events.

Predictive technology assessment tries to determine whether the push will equal the pull within a given lapse of time. As with TAARGET, the most credible assessments perform this determination quantitatively.

4.1.2 Project TAARGET

Some TA's are descriptive and/or cursory, others are sophisticated, quantitative statements regarding a particular technology. The TA for this study is derived from TAARGET, a large, methodologically quantitative, study of intelligent robotic technology. This study was a three year, \$12 million, international investigation that used the latest, most refined techniques currently available for a technology assessment. The original TAARGET report, as well as its 1983 update, are under privileged title.

Data Sources

The TAARGET data sources are relevant documents as well as interviews with qualified non-Soviet-Block opinionators around the world. Twenty-two thousand documents related to research, development, and application of intelligent robotic systems and subsystems were examined and analyzed by people technically trained in the material being examined. Documents/papers in French, German, Italian, Japanese, Swedish, and English were examined to determine their implications for technology development. The analyzed material was used to structure an interview program to confirm/disavow the hypotheses generated by the document analysis.

The principal tool used in the interview program was DELPHI - 14. This instrument permitted covert interviewing while generating reliable worst, best, and most likely time and performance estimates for subsequent input to the Decision Impact Risk Evaluation and Control Technique (DIRECT) simulator, which is discussed later.

One of the critical issues in developing a reliable consensus is the reliability of the opinionators consulted. A set of metrics were developed and tested on a random set of opinionators. These were found to be highly accurate in separating unreliable opinionators from reliable ones. The metrics were applied to a population of 4600 potential opinionators in the free world. Of these, 2000 were selected for interview. The greatest care was exercised by the project TAARGET team to ensure the reliability of its data sources.

Data Evaluation Methodology

After appropriately reliable data was obtained, it was processed by the risk assessment simulator, DIRECT, that was developed and refined during the late 1960's and early 1970's. As indicated in Figure 4-1, the input format is that of distributions taken from the DELPHI exercise. These are then piecewise convoluted and the terminal distribution is processed by a set of specially developed risk equations. Some of the outputs from DIRECT are given in Table 4-1. A typical example of a preliminary output from DIRECT is given in Figure 4-2a. A related, derivative output is shown in figure 4-2b. Both of these outputs are parameters in a quantitative reliability technology risk assessment.

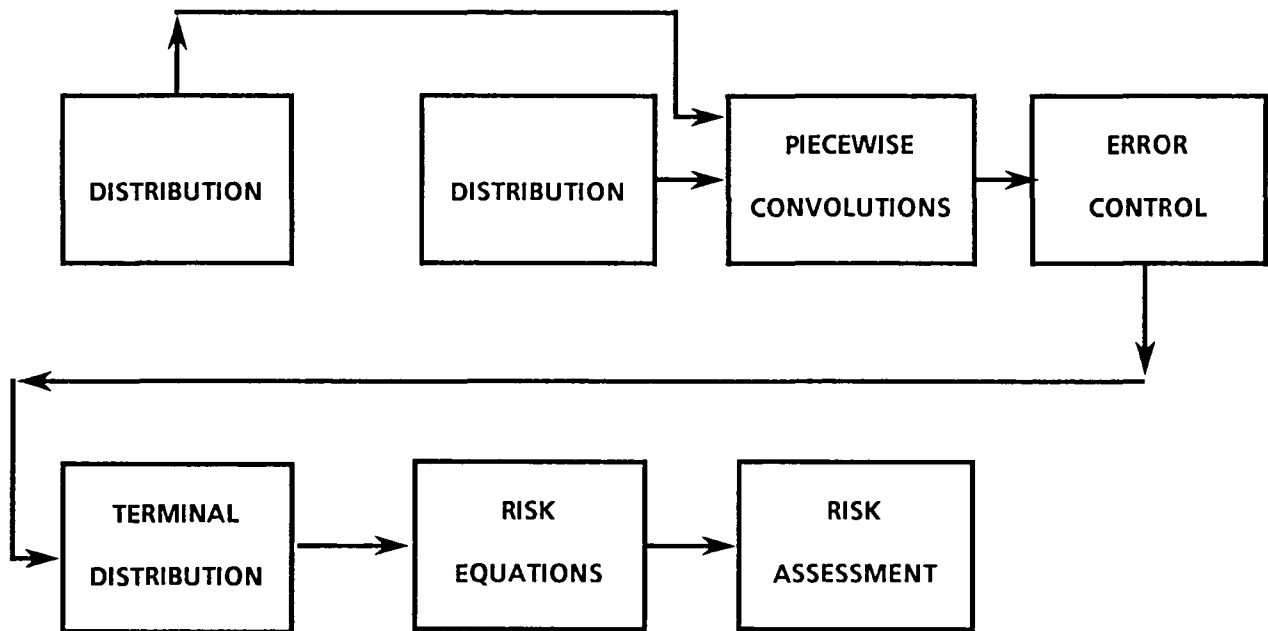
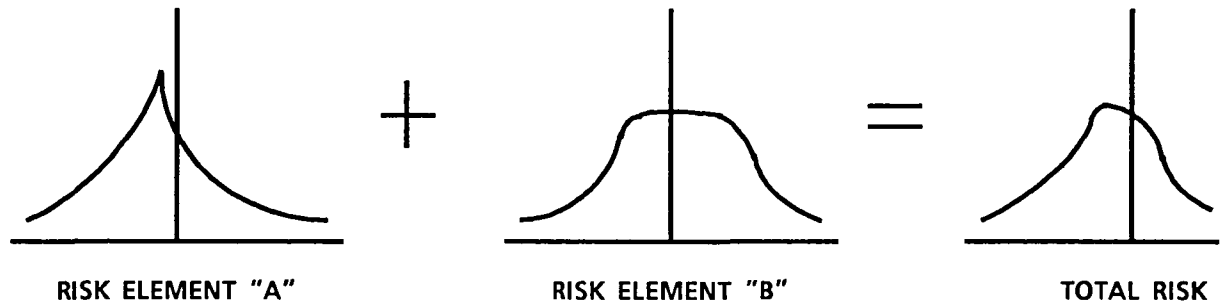


Figure 4 - 1
DIRECT: MAIN PROGRAM

- 1) COST / SCHEDULE / PERFORMANCE RISKS
- 2) RISK BUDGET FOR EACH ITEM OR SUBSYSTEM TO BE DEVELOPED / PRODUCED
- 3) CONTRACTOR FEE ON ANY TYPE OF INCENTIVE CONTRACT
- 4) RISK OF MAKING TARGET FEE / PROFIT ANY TIME DURING CONTRACT FULLFILLMENT
- 5) TOTAL PROGRAM IMPACT OF RISK ITEMS
- 6) COMPARATIVE EVALUATION OF RISK ABATEMENT STRATEGIES
- 7) OPTIMAL ALLOCATION OF RESOURCES (MANPOWER, DOLLARS)
- 8) RISK OF REACHING PROJECTED TECHNOLOGY GOALS
- 9) RISK OF MAKING A TARGET RETURN ON INVESTMENT (ROI)
- 10) PRESENT WORTH AND RISK OF PAY BACK PERIOD
- 11) MERGER RISKS
- 12) RISKS AND RISK IMPACT ASSOCIATED WITH CHANGES IN PERFORMANCE REQUIREMENTS

Table 4 - 1
PARTIAL OUTPUTS FROM DIRECT

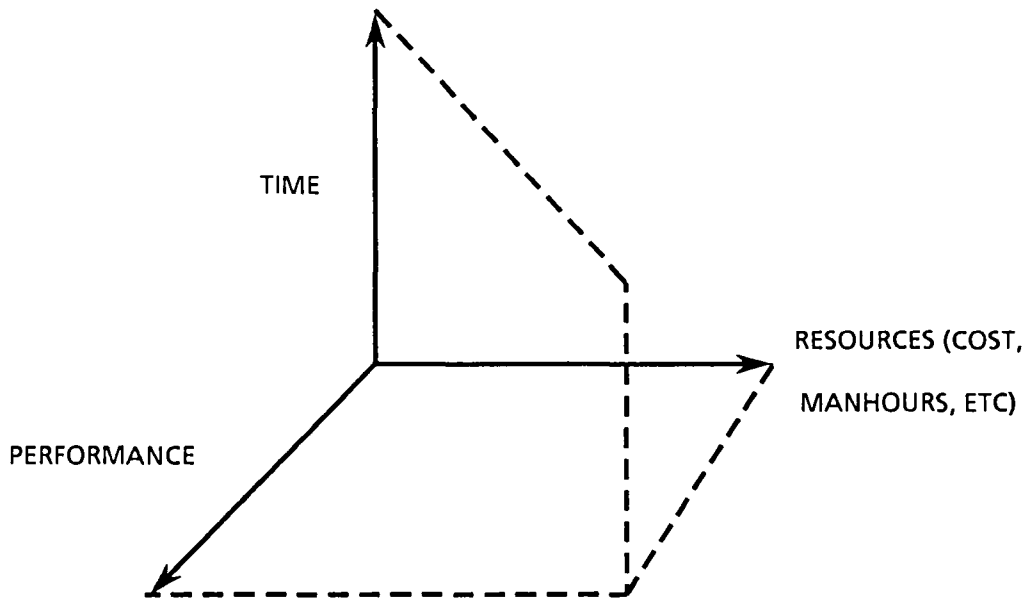


Figure 4-2a
INTERRELATION OF RISK PARAMETERS

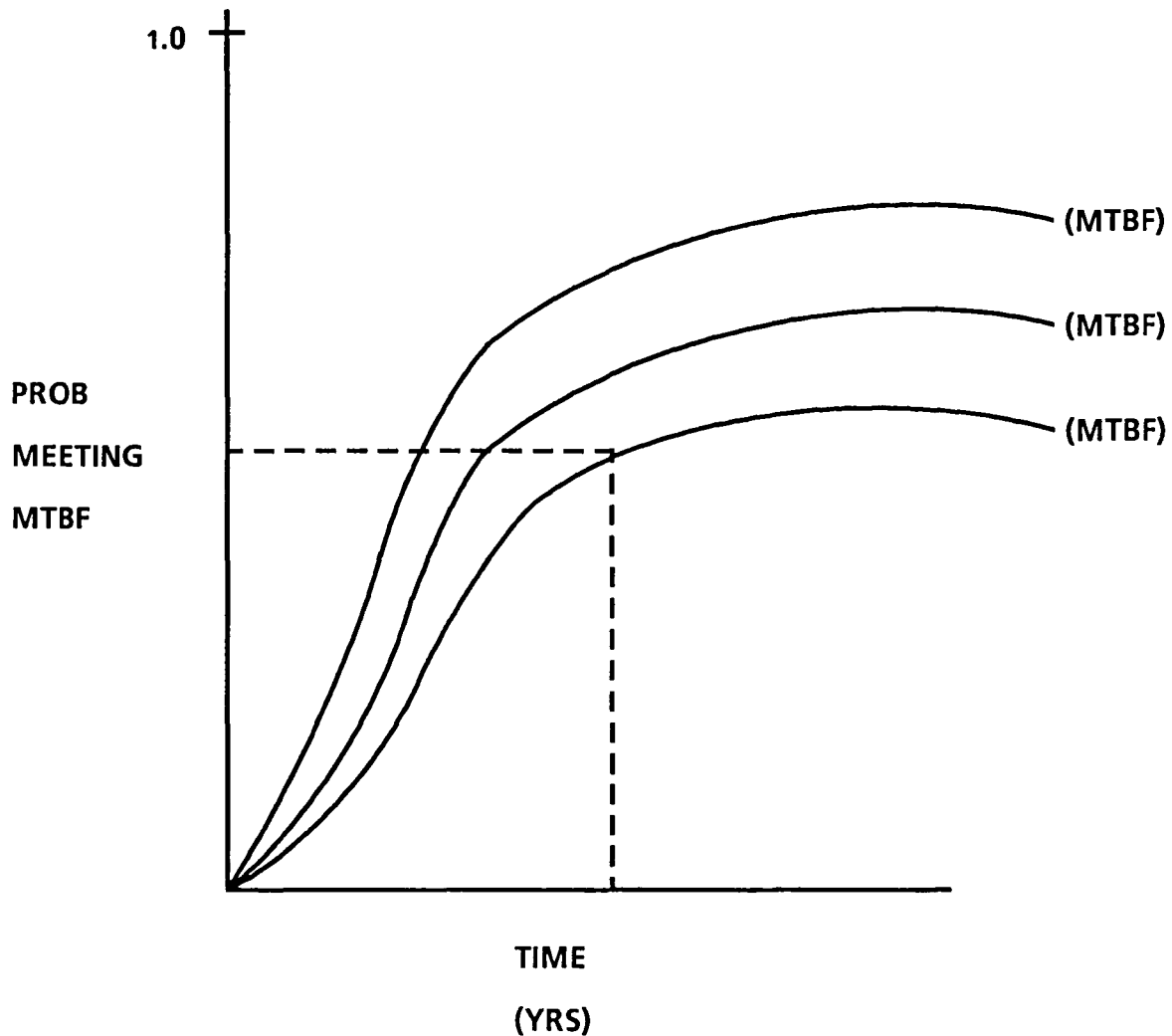


Figure 4 - 2b
TYPICAL DIRECT OUTPUT

DIRECT uses these preliminary results to simulate a PERT (or GERT) network with which impact analyses are performed. These involve quantitatively identifying the impact of socio-economic events (technology push conditioners) upon the rate of development to be expected from a given technology under differing socio-economic conditions. The results

of these analyses are usually a set of charts displaying best, worst, and most likely years in which differing types of demonstrations of the particular technology are to occur.

Most sophisticated predictive technology assessments use a set of well-defined event to define the maturity of a technology. Demonstrations are palpable events in technology development so the TAARGET study used a set of demonstrations to predict technology status. The types of demonstrations of a particular technology for which DIRECT predicts future status's are given in Table 4-2, together with the defining characteristics of the demonstrations





- **CONCEPT FEASIBILITY** 
 - Usually Stand Alone
 - Usually Non - Real Time
 - Crude, Undeveloped Interface(s)
 - No Form, Fit Optimization
- **MATURE LABORATORY PROTOTYPE** 
 - Pulled by Clearly Defined Technical Objectives
 - Frequently Embedded
 - Usually Real - Time
 - Interfaces Defined and Developed
 - Can Function as Proto - Engineering Baseline
 - Specific Potential Applications Can Be Defined
 - Accurate Quantitative Development Risk Assessments Possible
- **DEVELOPMENT ENGINEERING** 
 - Evolving Design
 - Constrained by Form, Fit and Economic Constraints
 - Well - Defined, Well - Developed Interface(s)
 - Real - Time
 - Frequently Embedded
 - Operational Parameters Testbed
- **PREPRODUCTION PROTOTYPE** 
 - Direct Basis for FAB and Assembly Requirements
 - Direct Basis for Production Cost Estimates
 - Field Testable Against Contracted Operational Requirements

Table 4 - 2 DEMONSTRATION TYPES AND CHARACTERISTICS

4.2 Summary of the OSI Technology Assessment

TAARGET results, suggest that it will not be possible to deploy a fully autonomous EV robot and OSI by the time of Space Station IOC. Therefore, we have defined a three phase approach to development of the EV robot and OSI. These three phases are marked by the technology pull of three separable sets of operational requirements. The system deployed at IOC will have sufficient autonomy to provide significant benefit to the Space Station crew. As time passes the system will evolve into the fully autonomous system described in Section 3.0. Table 4-3 characterizes the initial and final states of this system.

- | | |
|------|---|
| 1995 | <ul style="list-style-type: none"> ● Receive and understand an expanding set of question and/or command sequences. ● Report inability to execute a command sequence. ● Report valid reasons for inability to execute a command sequence. ● Report location. ● Report intended movement from one task space to another ● Report orientation in task space. ● Report status of own subsystems. ● Report fault-intollerant failures ● Receive, understand, and verify objectives menu ● Report plan of accomplishment (P. of A). ● Receive and understand corrections to P. of A. ● Infer and report intended changes in menu sequencing, with reasons. |
| 2010 | <ul style="list-style-type: none"> ● Identify and describe emergency situations |

Table 4-3
SCENARIO - DERIVED OSI OPERATIONAL REQUIREMENTS
(STRESSING SCENARIO)

Table 4-4a identifies the three phases of autonomy in our plan

PHASES (DEGREES) OF AUTONOMY

<u>Current</u>	<u>Phase 1</u>	<u>Phase 2</u>	<u>Phase 3</u>
<ul style="list-style-type: none"> Human Operator provides all control and problem solving functions Full Teleoperation 	<ul style="list-style-type: none"> Robot in Primary control loop Human is Planner Robot carries out plan in sequence prescribed by human Human Disabler 	<ul style="list-style-type: none"> Robot is both primary controller and planner Human provides intermediate goals Robot devises task to meet Human Disabler 	<ul style="list-style-type: none"> Robot provides own goals Human controls size and content of goal suite Human Disabler

Table 4 - 4a
GENERIC EVOLUTION OF AUTONOMY

A stepped decrease in human control and monitoring can be inferred from Table 4-4a, though Table 4-4b shows this stepped decrease more explicitly and also shows a stepped increase in robot autonomy

Most		
↓		
↓	Phase 1 (I O C)	Human Directed, (Low Autonomy)
↓		
↓	Phase 2 (2000)	Human Monitored (Moderate Autonomy)
↓		
↓	Phase 3 (2003-2007)	Human Instruction and Crisis Intervention (Maximum Autonomy)
↓		
Least		

Table 4 - 4b
DEGREES OF OSI

These phases into which the technology pull divides OSI development are based upon degrees of robot autonomy These phases will, in turn, be translated into sets of

functional requirements, each of which is both OSI - and Phase - specific. Such translation is accomplished in the following Section.

4.2.1 Phase 1: Human Directed

If the E.V A. robot is expected to carry out a plan prescribed in detail by a human controller under conditions of intelligent monitoring by that controller it must meet, at least, the following functional requirements.

- * ● Receive/understand limited set of voice question/command sequences
- * ● Receive/understand bar code graphics also seen by human operator
 - Nonvocal copy-back to operator of question/command sequence in synonymous vocabulary
 - Nonvocal copy-back to operator of bar code graphics
- * ● Infer current position and terminus coordinates for next transit
 - Report location and transit orientation by nonvocal transmission of "perceived" bar code/reflectors
 - Report orientation to task space by nonvocal transmission of perceived bar code and tactile pressure sensors
 - Report completion of each step in task sequence by bar code.

Of the above requirements, the first four and the last three are OSI-specific. The key technologies supporting these requirements were selected on the basis of their evolutionary capacity. These technologies are:

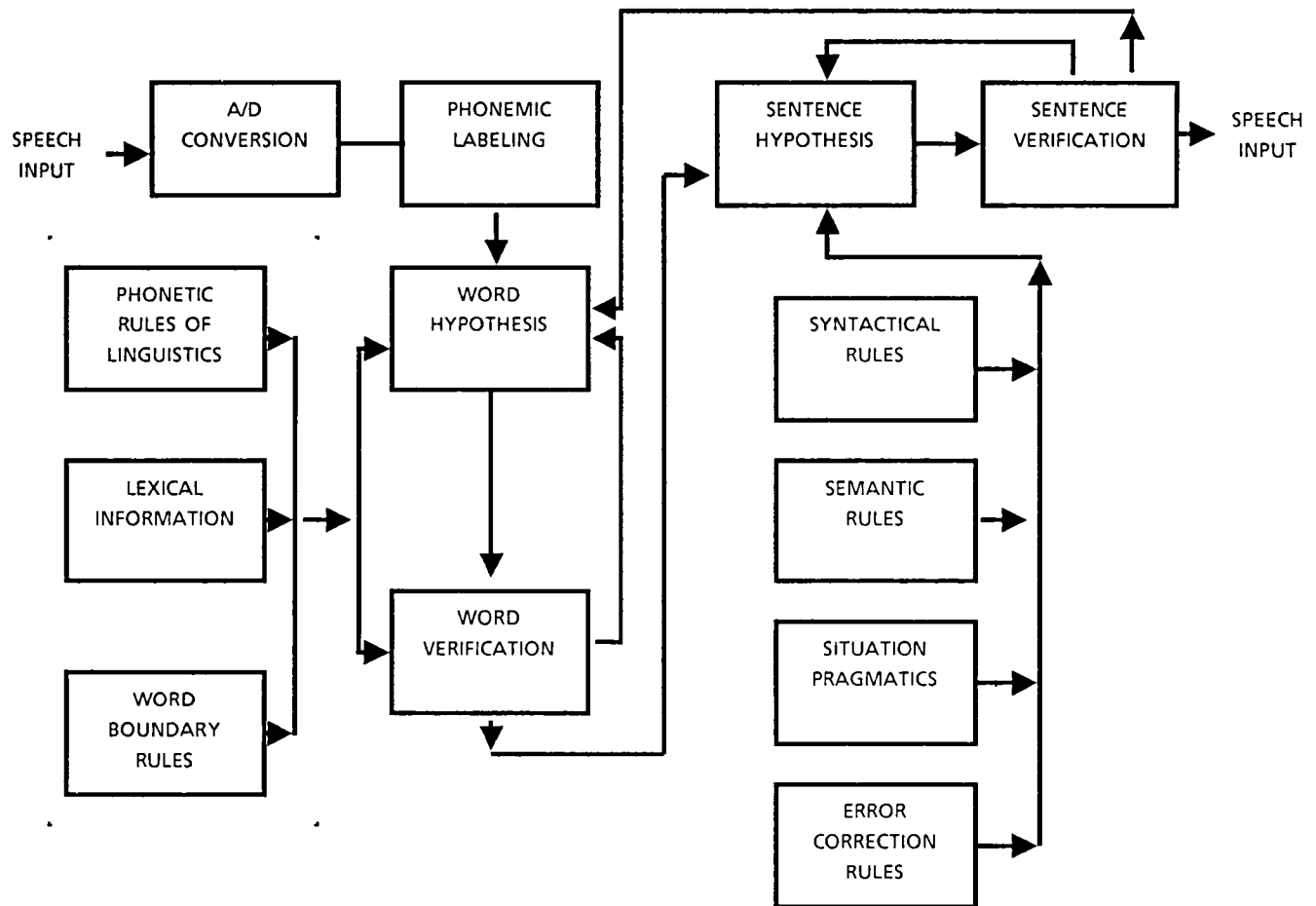
- * ● Voice Intentionality Constrained Evaluator (VICE)
- RF/Optical Dual Mode Communication Link
- * ● Knowledge-Based 2-D Image Understanding/Semantic Processor
- * ● Inference Engine
- * ● Integration with Primary Controller

These technologies were selected not only for their pullability but also because, if pushed, they would permit a "nonscarring" evolution with respect to the next phase. One

technology listed is not preceded by an asterisk. This is because it was considered by the TAARGET team to be technologically mature

VICE is an "interim" nonscarring technology being developed at Boeing's Artificial Intelligence Research Center as well as at at least two other laboratories overseas. It consists of introducing a small number of synthetic particles into natural speech in order to disambiguate words or phases that are normally clarified by visually observed, situational context. Thus, if future speech understanding involves the functions found in Figure 4-3 then such particles would be a part of the "situation pragmatics" or the error "correction rules".

Figure 4-3
FUTURE SPEECH RECOGNITION

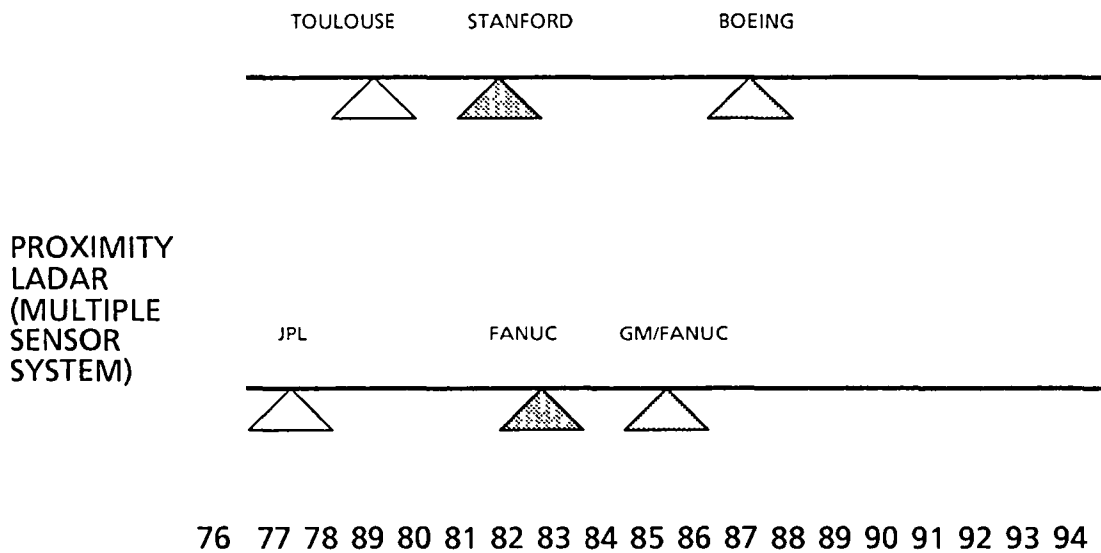


Knowledge-Based Image Understanding (KBIU) uses intra- and interframe (picture) semantic relationships as well as some of the techniques of intensional logic to understand the nature of a scene or series of scenes. While image understanding technology has been pushed by the DARPA initiative in that area, it is still in need of both technology pull and corresponding push.

To do the logic required by the KBIU as well as making inferences about current and terminal positions, an "inference engine" that is modularly up-gradable is required.

Robot control of its primary loop (RCPL) presupposes technology pull and push that is related to but apart from that of OSI. For a robot to carry out the step-by-step commands associated with Phase 1 OSI, it must be able to control its movements sufficiently to avoid obstacles and handle complex pressure-sensitive tasks. To do these adequately, technology in the areas of TV camera-augmented Khatib control (TVKC) and LADAR proximity sensing must be pulled and correspondingly pushed. The technology push for both of these was addressed by the Project TAARGET team. Their most-likely estimates are given in Figure 4-4.

Figure 4 - 4
RCPL SPECIFICATION OF TECHNOLOGY PUSH FOR OSI PHASE 1



4.2.2 Phase 2: Human Monitored

If an EVA robot is expected to plan and carry out intermediate goals set by a human controller, then several machine intelligence technologies must be pulled by these functional requirements:

- * ● Receive/understand connected speech with expanding vocabulary
- * ● 3-D acquisition of objectives in space (with bar code backup)
- * ● Vocal copy-back in synonymous language of all transmissions from operator to robot.
- * ● Nonvocal copy-back to operator of all transmissions to robot.
- * ● Plan optimal/sub-optimal sequences for fulfilling operator goals.
- * ● Initiate and execute unplanned obstacle avoidance
- Periodic recording of all robotic subsystems status for eventual copy-back
- Robot communicates its maintenance requirements vocally and nonvocally
- * ● Robot perceives and communicates a limited set of crisis conditions to operator.

Nearly all of the items on the list are preceded by an asterisk, i.e., considered pullers. Two that are not starred are actually derived from others on the list that are. However, only the first, third, and fourth items are directly OSI pullers.

The technologies pulled by these three are given in the list below.

- Voice Recognition
- * Speech Understanding
- * Language Representation
- * Natural Language Understanding
- * Analogical Reasoning
- Monotonic Reasoning
- * Nonmonotonic Reasoning
- * Speech Synthesis/Translation

Again, these were selected not only for their pullability but also because, if pushed, they would permit a "nonscarring" evolution with respect to the third phase. Those items preceded by an asterisk are pullable and, in most cases, in need of technology push from items such as economic conditioners. Of the items on the list, perhaps three need some description. Language Representation, Monotonic, and Nonmonotonic Reasoning.

Like everything else perceived by humans, language must be properly symbolized in order to be manipulated for understanding and synthesis. This is particularly a problem for machine intelligence if the representation uses excessive storage and processing capability. Efficient schemes for symbolizing and manipulating strings of language "data" must be devised and tested against human criteria for performing the same manipulative exercise.

"Monotonic" and "nonmonotonic" reasoning are synonymous respectively with deductive logic (usually the first order predicate calculus) and the logic of belief and "hunch" statements. Both are required in order for a machine intelligent robot to represent and conceptually synthesize its replies to a human interrogation.

It should be noted that the speech and language requirements placed upon the Phase 2 robot in order to facilitate OSI neither negate nor render obsolete the software for voice recognition developed for Phase 1. Rather, it builds upon it, improving each of the function boxes in Figure 4-3.

4.2.3 Phase 3: Human Instruction and Crisis Intervention

An EV robot required to provide its own goals (within limits) and then devise strategies to meet these goals must not only build on the development of Phases 1 and 2 but also be capable of these additional functions.

- * ● Learn New ..
 - Objects
 - Properties
 - Relations
 - Events
 - Situations (Internal/External)
 - Human Voice Prints/Imagery

- * ● Autonomously Change Its Databases
 - Know When Deficient
 - Know Required Information
 - Know How to Reorganize File Structures
 - Know How to Merge/Sort
- * ● Autonomously alter its primary and/or secondary control loops as functions of learning
- * ● Repair/Maintain Itself.

All of the requirements listed above are technology pullers. Essentially the Phase 3 robot would be a vehicular, multidimensional expert system. The robot's knowledge base and its manipulation would not only have depth and breadth, but would also possess a floatable modularity, permitting limited inductive changes in its software

The OSI-specific puller is involved with learning. The abilities to adapt to new surroundings and to solve new problems are important characteristics of intelligent entities. These can be subdivided into two equally important components; acquisition of new knowledge and problem solving both to integrate the new knowledge and to deduce new information in the absence of presented facts

The functional requirements listed above can be translated into these very pullable technologies:

- * ● Learning Systems
- * ● Adaptive Database Management
- * ● Self-Adaptive Control
- * ● Floating Architectures
- * ● Reflective Interpretation
- * ● Self Repair

These technologies almost correlate one-for-one with the functional requirements that pull them. Again the OSI specific technology is learning systems, since it is expected that much of the robot learning will occur by means of an astronaut teacher.

4.3 Phased OSI Technology Push

DIRECT was used to produce worst, best and most likely estimates of the years in which the four types of demonstrations discussed earlier would occur for OSI-specific technologies. However, only the most likely estimates are presented in this report. The primary reason for this is the highly parametric nature of "best" and "worst" estimates. That is; such estimates are related to a set of complex, interrelated, technical, economic and social factors the values of which must be varied over a broad range and in several dimensions. TAARGET used both macro- and microeconomic models to handle the interrelationships and to arrive at a spectrum of worst case and best case estimates. Presentation of these estimates requires many pages of explanation, tables and graphs. Instead of presenting this voluminous material, the following relationships can be used as a rough estimate of the impact of economic changes on the occurrence of demonstrations of OSI-related technology.

1. Influence of decreased funding

If the funding, from all sources, supporting development of a very nonmature technology is reduced for 12 months then the influence on the date of occurrence of technology demonstrations is:

% reduction	add to "most likely" date
0 - 15	12 - 18
16 - 22	19 - 30
23 - 33	31 - 41
34 - 50	42 - 60

2. Influence of increased funding

If the funding, from all sources, supporting development of a very nonmature technology is increased for 12 months then the influence on the date of occurrence of technology demonstrations is:

% increase	subtract from "most likely" date (months)
0 - 15	8 - 12
16 - 22	13 - 20

23 - 33
34 - 50

21 - 28
29 - 36

Most of the OSI technologies for which a "push" assignment was given fall in the "nonmature" or "very nonmature" categories defined by TAARGET.

4.3.1 Phase 1 Push

Figure 4-5 shows the technology push and estimated technology demonstration dates for four OSI-related technologies. Only the first two of these are needed for the Phase 1 OSI. The third, Inference Engine, will be required for the Phase 2 OSI development.

The project TAARGET team developed a set of metrics to quantitatively describe technology performance at the time of the statusing demonstrations. In effect, these metrics constitute the minimum performance of the system expected at the time of the preproduction prototype demonstration. Table 4-5 gives the metric for each of the Phase 1 OSI supporting technologies

Figure 4 - 5
OSI PHASE 1 TECHNOLOGY PUSH

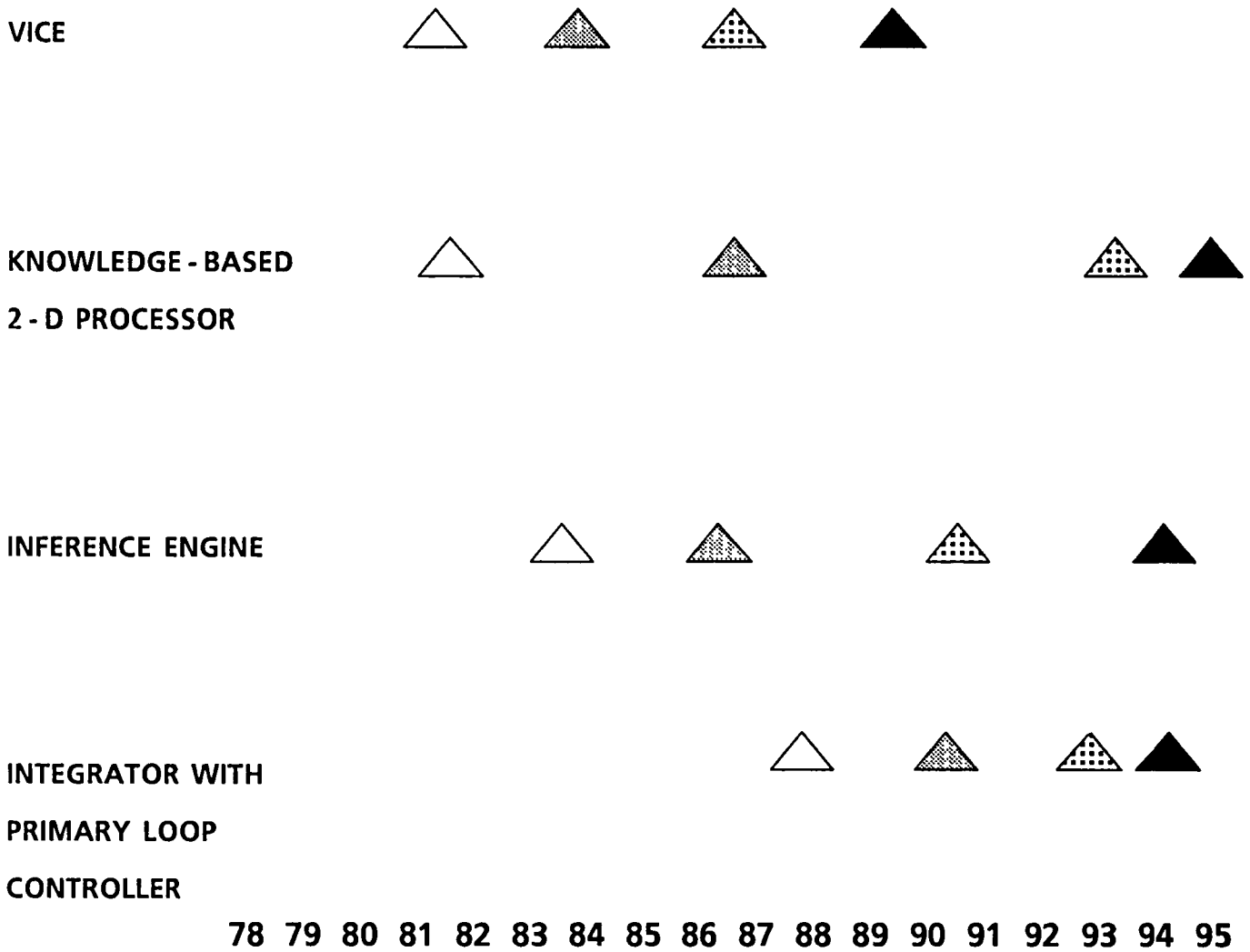


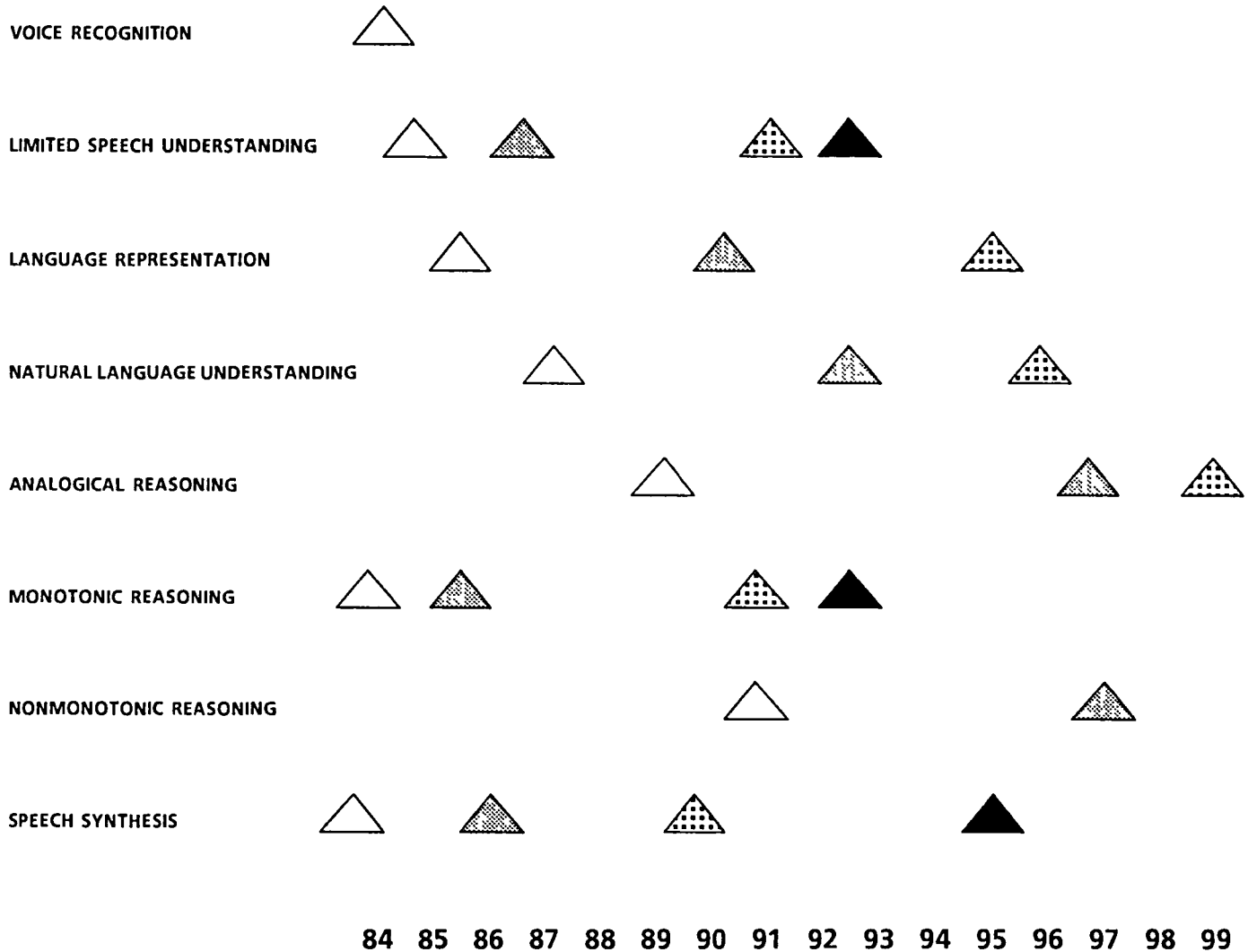
Table 4 - 5
METRICS FOR OSI PHASE 1 TECHNOLOGY PUSH

VICE	<ul style="list-style-type: none"> • 2000 WORD VOCABULARY • 1% ERROR RATE • PROCESSING SPEED = HUMAN
KN. BASED 2 - D PROCESSOR	<ul style="list-style-type: none"> • 4 FRAMES PER SECOND • INTERFRAME ANALYSIS \geq HUMAN • \leq 200 RULES • ACCURACY = HUMAN
INFERENCE ENGINE	<ul style="list-style-type: none"> • MONOTONIC REASONING • 20 NON - CHAINED INFERENCES PER MINUTE • ACCURACY = HUMAN

4.3.2 Phase 2 Push

Figure 4-6 presents the push for the supporting technologies for the phase 2 OSI. The most likely estimates make it clear that preproduction prototypes for some of these will not be available until after the year 2000. This is especially true for analogical and nonmonotonic reasoning.

Figure 4 - 6
OSI PHASE 2 TECHNOLOGY PUSH



This figure suggests that appropriately funded research and exploratory development efforts should be begun as soon as possible and continued for several years in these areas.

- language representation
- natural language understanding

- analogical reasoning
- nonmonotonic reasoning

This recommendation is based not only on the estimated slip into the next century of OSI-significant demonstrations but on the fact that all four technologies are critical drivers of subsequent robotic technology development.

A set of performance statusing metrics for Phase 2 was developed as shown in Table 4-6. Like those of Phase 1, they were developed after interrogation of opinionators in real-time applications throughout the United States and in several foreign countries.

Table 4 - 6
METRICS FOR OSI PHASE 2 TECHNOLOGY PUSH

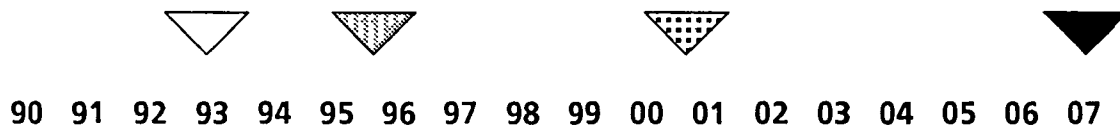
SPEECH SYNTHESIS, SPEECH, LANGUAGE UNDERSTANDING	● 5000 WORD VOCABULARY
	● 2% ERROR RATE
	● PROCESSING SPEED = HUMAN
ANALOGICAL REASONING	● 8% ERROR RATE = HUMAN
	● ~ 30 INFERENCES PER MINUTE
NONMONOTONIC REASONING	● 19% ERROR RATE = HUMAN
	● 60 INFERENCES PER MINUTE
MONOTONIC REASONING	● 2% ERROR RATE = HUMAN
	● 20 INFERENCES PER MINUTE

4.3.3 Phase 3 Push

The strictly OSI-supporting technology for Phase 3 is that of learning systems. Figure 4-7 shows that the "most likely" estimates for this technology will not produce a real-time preproduction prototype until 2007. The reasons for this are many and complex. While

Samuels (1963 and forward), Newell (1960 and forward), Lenat (1977), Evans (1981) and Winston (1979) have all made progress in this area, it is still very poorly understood and therefore, poorly developed.

Figure 4 - 7
OSI PHASE 3 TECHNOLOGY PUSH FOR LEARNING SYSTEMS

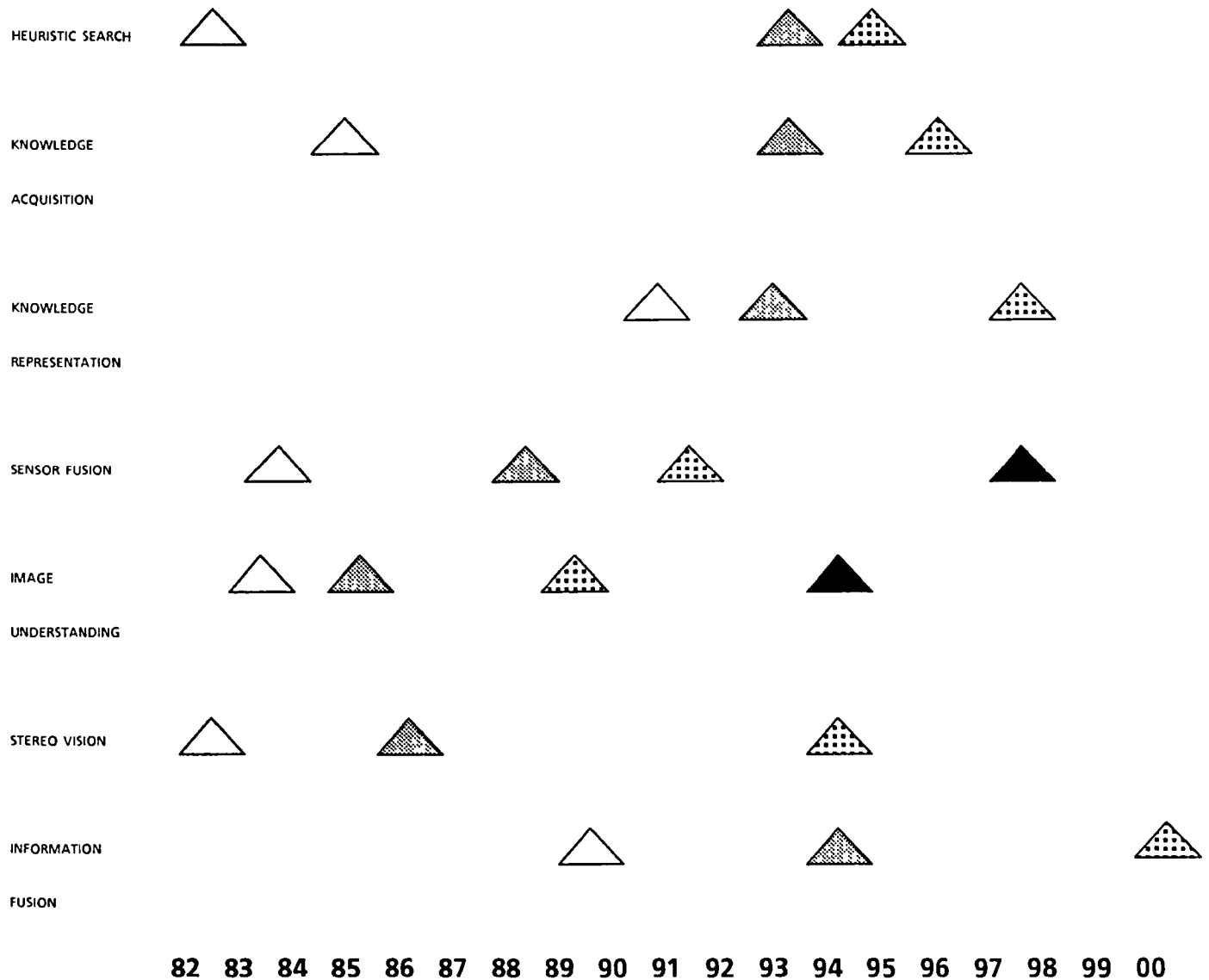


Part of the problem involved development of other, not strictly OSI, technology during the Phase 1 and Phase 2 periods. These are

- sensor fusion
- image understanding
- stereo vision
- information fusion
- heuristic search
- knowledge acquisition
- knowledge representation


Figure 4-8 and Table 4-7 give the push assessments for these technologies along with the metrics used to measure their status

Figure 4 - 8 OSI PHASE 3 TECHNOLOGY PUSH



In summary, learning is a problem-solving activity that depends heavily upon the development of intelligent vision systems as well as upon heuristic search and knowledge representation. It is, therefore, obvious that investigations in each of these areas must be accelerated and broadened.

Table 4 - 7
METRICS FOR OSI PHASE 3 TECHNOLOGY PUSH

HEURISTIC SEARCH	 <ul style="list-style-type: none"> • ACCURACY = HUMAN TEST SUBJECTS • SPEED = HUMAN TEST SUBJECTS • SEARCH COMPLEXITY = GAKY • DYNAMIC UTILITIES (Good)
KNOWLEDGE ACQUISITION	HARTLEY - MITCHIE - GOOD METRIC
KNOWLEDGE REPRESENTATION	(NONE AVAILABLE)
SENSOR FUSION	POLITOPOULOS CRITERION
IMAGE UNDERSTANDING	DORROUGH/HOLBEN CRITERION
STEREO VISION	NONE
INFORMATION	NONE

4.4 Alternative Paths to Robotic Autonomy

The position taken in this study is that maximum likelihood of success in developing the EV robot and its OSI and that maximum applicability of the developed technology to other fields will result if the basic approach is to make use of evolving machine autonomy throughout the development process

However, an alternative development path would be to evolve from current teleoperation technology. This Section examines that alternative. Before addressing some of the questions related to the "movement" from teleoperation to intelligent autonomy, a characterization of each seems required.

A teleoperated robotic system is one that utilizes cybernetic anthropomorphic machine systems (CAMS) technology in order to permit the human operator to transmit his or her intelligence and dexterity through the machine and to the task. All decision-making capability resides with the human controller. A servo-control system usually transmits a small proportion of the load force to the operator's hand(s) thus giving him or her "instinctive control" of the job. Frequently, six degrees of freedom are present. These include horizontal extension, hoist, azimuth rotation, yaw, pitch, and roll.

'Machine autonomy' is defined in the National Bureau of Standards Dictionary as "the ability to function as an independent unit over an extended period of time, while performing a variety of actions and while responding to stimuli produced by integrally contained sensors."

As characterized, the two concepts are far apart. Neither implies the other. It is, therefore, logical to ask whether or not there is some causal or perhaps evolutionary relationship between the two.

Pursuing this direction of thought leads to the following considerations: Human teleoperators have succeeded in using teleoperations to program a robot to carry out a series of procedures for executing a particular set of rather simple tasks (e.g., Kinsey, et al, also, Yonemoto, Takeuchi, and Cornfield). A few, more complex, systems have been demonstrated by NASA with respect to planetary landers. By some, therefore, it is regarded as reasonable to believe that a completely specified set of deterministic procedures which are related to a predetermined spectrum of task spaces for a given robot can make that robot autonomous in the sense defined above.

There are two major difficulties with this position. 1) It requires either that the number and kind of tasks performed be low and simple or that the computational burden be prohibitively high; and more significantly 2) the technology pull from such a position lies within the range of zero to very low.

An alternate position (and one with large technology pull) is to assume that autonomy involving a maximal number and complexity of tasks together with manageable computational burdens will only come about by improving the supporting technologies of

machine intelligence while reserving teleoperation for 1) the small number of intense crisis situations that may arise in the course of a mission, and 2) robot learning.

This latter is the Boeing position. It is supported by the responses from qualified opinionators within research communities around the world. To these was posed the following question by members of Project TAARGET:

"AS DEFINED, CAN AUTONOMOUS MACHINE (ROBOTIC) TECHNOLOGY EVOLVE NATURALLY (i.e., WITHOUT MAJOR TECHNICAL INNOVATIONS/CHANGES) FROM CURRENT TELEOPERATED ROBOTIC TECHNOLOGY?"

Their responses, summarized in Table 4-8, make it clear that almost all individuals involved in robotic research or its supporting technologies agree that autonomous robotic technology development will occur only by means of inventions/innovations apart from teleoperation.

RESEARCH COMMUNITY*	YES (%)	NO (%)
Artificial Intelligence Lab (MIT Cambridge)	0	100
Robotics Institute (Carnegie - Mellon)	0	100
Fraunhofer Institut (Karlsruhe)	3	97
Institute für Informatik (Bonn)	5	95
Institute für Informatik (Karlsruhe)	2	98
Labatoire Automatique (Montpellier)	0	100
Comp Science Dept , G M Research Labs (Warren)	0	100
A I Center, SRI International (Menlo Park)	2	98
Robot Research Laboratories (Kingston)	0	100
School of Artificial Intelligence (Edinburgh)	0	100
Robotics Section, Hitachi Central Research Laboratory (Tokyo)	0	100
Robotics Laboratory, Institute of Tech (Tokyo)	1	99
Electrotechnical Lab, Science and Tech Agency (Tokyo)	0	100
Central Laboratory, Kawasaki Heavy Industries (Tokyo)	0	100
Univ of Maryland Comp Sci Center (College Park)	4	96
Stanford Artificial Intelligence Lab (Palo Alto)	0	100

* Minimum Sample Size = 4

Table 4 - 8

**OPINIONATOR RESPONSE TO FEASIBILITY OF AUTONOMOUS ROBOTS
EVOLVING FROM TELEOPERATION**

5.0 CONCLUSIONS AND RECOMMENDATIONS

The following major conclusions can be drawn from the results of this study. It is technically feasible to develop an automated OSI by about 2010 to perform efficient supervisory management functions for an EV robot. The results of this study show that it is technically feasible to develop an initial, fairly rudimentary EV robot and OSI system by about mid 1990, and a sophisticated, efficient, and convenient system by about 2010. The initial OSI system would have a limited supervisory capability and would be largely experimental in nature.

The artificial intelligence technologies that will need to be pushed to develop OSI capabilities are:

- Language representation,
- Natural language understanding,
- Analogical reasoning, and
- Nonmonotonic reasoning.

This study also showed that an EV robot will have great potential for relieving astronauts of routine and hazardous tasks and for increasing the level of EV activity in support of the Space Station. To achieve this, the OSI for an EV robot will facilitate high-level communication between the astronaut and the system.

To develop the complex systems and interactions between humans, hardware and software that are needed for the EV robot OSI, we recommend that NASA initiate an advanced development program in this area. The program could include a concept definition phase, using requirements identification and trade studies. The trades would include the partitioning between human and robotic activities, the partitioning of processing between the Space Station DMS and the onboard robot processor, the use of fixed versus portable or dispersed controls and displays, the teleoperation versus autonomous robot operation trades, programming language trades, RF versus onboard data storage trades, robot design trades that affect OSI, Space Station design trades that affect OSI, and trades on the rate of evolutionary progression of the robot-OSI systems.

The second phase could include development of candidate OSI hardware and software concepts. To facilitate this phase, it is recommended that a simulation of EV robot body dynamics and manipulator actions be developed and coupled with models of candidate OSI software, and controls and display hardware. The simulation of the EV robot would provide graphic outputs through use of computer-generated imagery as well as quantitative measures of performance. Through use of this tool, modelled OSI systems could be evaluated by human operators and modified to obtain more and more satisfactory interaction. When a workable interaction is reached with these models, the design requirements for an OSI demonstrator could be extracted.

The third phase of the program could demonstrate and further develop interactions between an EV robot and human users. For this phase it is recommended that a neutral buoyancy facility test bed be used. The robot for such a test bed could initially be an off-the-shelf aquatic robot modified to include necessary on-board processing. The candidate OSI software could be resident in laboratory computers and in processors associated with the tankside control station and robot berthing port. The test site control station could serve as a test bed for further development of candidate controls and display hardware. Using this test bed facility, the hardware, software, and techniques for OSI supervision of a robot could be further developed and demonstrated. Operations where the robot supports an EVA astronaut could be developed and demonstrated by an astronaut working in the tank with the robot which is supervised by control station inputs through the candidate OSI.

Such a program requires detailed implementation planning to bring the necessary facilities, test articles, hardware, software and personnel together into a fruitful effort. Realistic goals and milestones need to be established as well as test evaluation criteria. Early initiation of such a program by NASA would not only help develop the EV robot-OSI concept and the associated technology but would also develop confidence in the concept by the potential Space Station users.

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